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THESIS

CODED PERFORMANCE OF A FAST FREQUENCY-HOPPED
NONCOHERENT BFSK RATIO STATISTIC RECEIVER OVER
A Rician FADING CHANNEL WITH PARTIAL-BAND
INTERFERENCE

by

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September, 1992

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**CODED PERFORMANCE OF A FAST FREQUENCY-HOPPED NONCOHERENT
BFSK RATIO STATISTIC RECEIVER OVER A RICIAN FADING CHANNEL
WITH PARTIAL-BAND INTERFERENCE**

by

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ABSTRACT

A frequency-hopping binary frequency shift keying (BSFK) ratio-statistic receiver with multihops per data bit is an effective electronic counter-countermeasures (ECCM) system against partial-band jamming interference. Interference is modeled as Gaussian noise. Orthogonal binary signaling and independent fading diversity is considered over frequency-nonselective, slow fading Rayleigh, Rician, and Gaussian channels. A forward error correcting coding scheme is implemented for a 1/2 rate convolutional code algorithm. The probability of bit error is examined for different levels of diversity, thermal noise, severity of fading, fraction of bandwidth jammed, and jamming power. Uncoded and coded system comparisons are done to determine worst case performance.

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DEDICATION

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I. INTRODUCTION

A frequency-hopping (FH) binary frequency-shift keying (BFSK) with multihops per bit is an effective electronic counter-countermeasures (ECCM) system. It provides low probability of intercept (LPI) and antijamming capability (AJ) for the communication channel. An effective strategy called partial-band noise jamming is used against this communication system [Ref.1:pp.471].

The principal requirement of the communication system is to transmit the source information of a binary data sequence by means of M-ary FSK over the channel. We consider that the channel is modeled as a fading dispersive channel due to multipath problems and the jammer as an additive Gaussian noise. The addition of a frequency-hopping scheme provides some immunity against interference over an allowed system bandwidth of W Hz.

Many different receiver structures for multihops per data bit of FH/MFSK waveforms transmitted over the channel have been considered in order to counter or mitigate the effects of partial-band jamming and fading dispersive channels. Examples of such receivers are: 1) square-law non-linear combining with adaptative gain control, 2) soft-limiter amplitude control, 3) self-normalizing soft decision, and 4) ratio-statistic

combiner.

Keller and Pursley analyzed a ratio-statistic combining receiver in a frequency hopping spread spectrum system in the presence of partial-band interference for a channel with Rayleigh fading [Ref.2:p.145]. Their paper shows that the spread spectrum scheme provides some immunity to jamming and interference, and the ratio-statistic combining technique improved immunity to partial-band jamming.

Riley analyzed the performance of a fast frequency hopped noncoherent BFSK receiver with ratio-statistic combining over a Rician fading channel with partial-band interference [Ref.3]. This thesis involves a comparison of the performance of envelope detectors versus square-law detectors, and the following conclusions were established: 1) ratio-statistic combining used in conjunction with diversity limits degradation due to fading and partial-band interference and generally provides an improvement in overall performance, 2) Rician fading and partial-band interference have a significant impact on receiver performance, 3) ratio-statistic combining provides protection against partial-band interference as diversity is increased, and 4) for diversity of three and four, the receiver using envelope detection performs better than that of a receiver using square-law detection.

Prior work by the authors [Ref.2]-[Ref.3] analyzed the performance of uncoded systems using soft decision receivers in the presence of fading channels with thermal noise and

partial-band noise jamming.

The purpose of this thesis is to show the performance of a forward error control (FEC) coded system using a ratio-statistic combining BFSK receiver with envelope or square-law detection in a fading channel with partial-band interference. The present work examines the probability of coded bit error versus different environment cases such as diversity, thermal noise, jamming duty factor, signal to jamming ratio, direct signal to noise ratio, diffuse signal to noise, envelope and square-law detection. Performance curves are obtained for coded communication systems.

II. COMMUNICATION SYSTEM DESCRIPTION

A. MODEL.

The general structure of the communication system to be evaluated is illustrated in Fig. 1.1. The system is characterized by an error probability which depends on the characteristics of the transmitter, the channel, and the receiver.

This model is comprised of the following elements:

- Sequence of binary messages.
- Encoder.
- M-ary FSK modulator.
- Spread spectrum hopper.
- Fading channel.
- Partial-band interference modeled as additive Gaussian noise.
- Thermal noise.
- Spread spectrum dehopper.
- M-ary FSK demodulator with square-law or envelope detection.
- Ratio-statistic soft decision.
- Decoder.
- Error corrected binary sequence message.

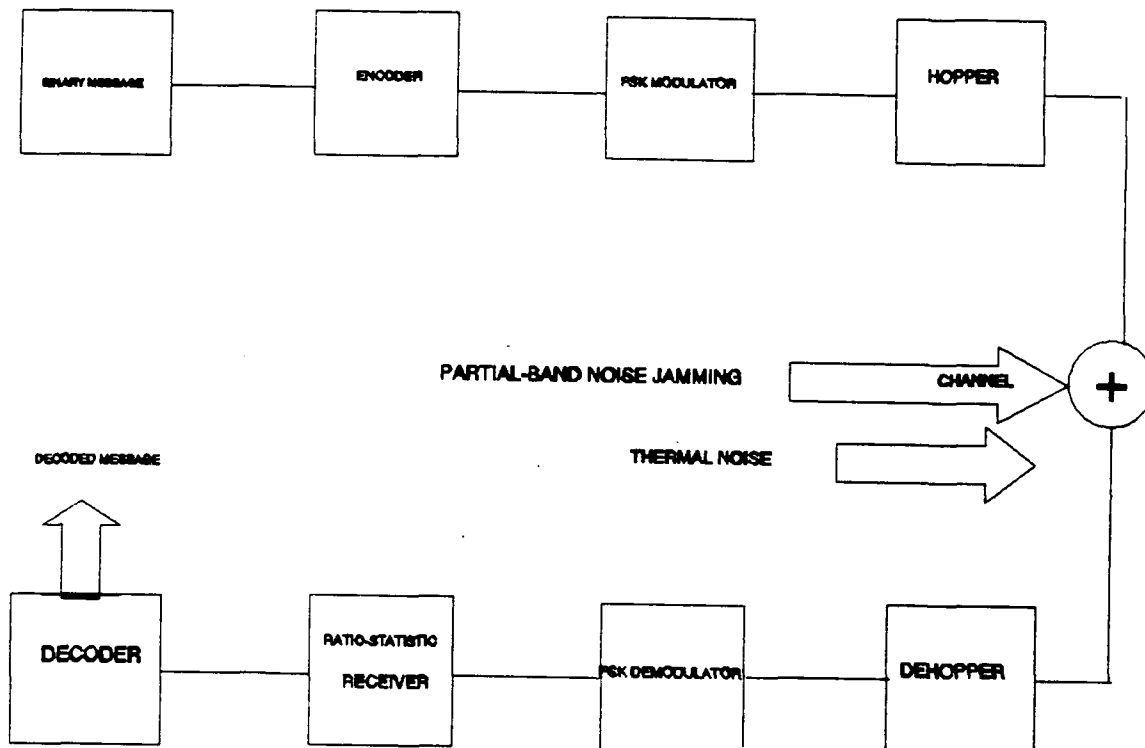


Figure 1.1 Communication System Model.

B. PARTIAL-BAND INTERFERENCE.

In an interference environment, frequency hopping spread spectrum (FHSS) systems are used to reduce receiver performance degradation due to different type of jammers. In order to explain the **partial-band interference** term, it is necessary to understand the **barrage noise jammer**. This jammer transmits bandlimited Gaussian noise with a one sided power spectral density (PSD) of N_j W/Hz and the jammer power spectrum covers exactly the frequency range of the spread spectrum signal. The effect of the barrage noise jammer on the system is to increase the Gaussian noise at the output of the receiver. If FHSS is present, the jamming power is more efficiently used by transmitting all the available power in a limited bandwidth which is smaller than the spread spectrum signal bandwidth [Ref.4:pp.558]. This strategy is called **partial-band interference** and the fraction of the spread spectrum signal bandwidth which is jammed is denoted by γ . For total jamming power J and a FHSS signal bandwidth of W , the barrage noise jammer one-sided PSD is $N_j = J/W$ over the entire band, while the partial-band jammer one-sided PSD is $N_j/\gamma = J/\gamma W$ over a bandwidth γW . The total two-sided noise power spectral density is $\gamma^{-1} N_j/2 + N_o/2$. The partial-band interference is assumed to be present in each branch of MFSK demodulator, and the fraction γ of the spread spectrum corrupted is assumed to be the same for an entire symbol. The fraction γ represents

the probability that partial band interference is present in all M branches of the receiver, and $1-\gamma$ is the probability that partial-band interference is not present in all branches of the receiver.

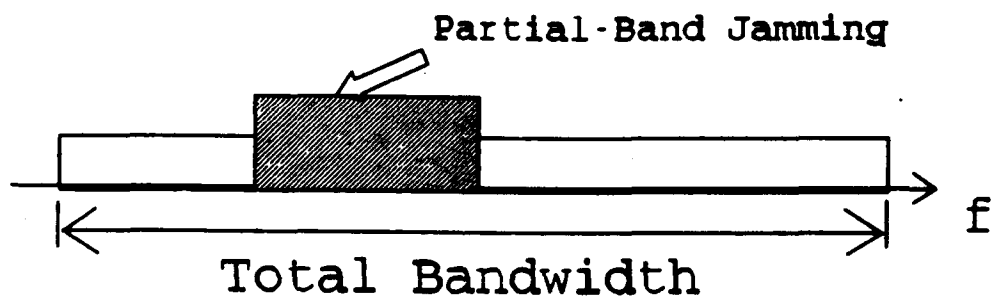


Figure 1.2 Barrage and Partial-Band Interference

C. **FADING MULTIPATH CHANNEL.**

In the multipath propagation model for the channel, the fading phenomenon is a result of the time variation in the signal phases. Randomly at times, signals can add destructively. When that occurs, the resultant received signal can be significantly attenuated. At other times, the incoming signals add constructively so that the received signal is large. These amplitude variations in the received signal are called **signal fading** and are due to the time variant multipath characteristic of the channel[Ref.5:pp.457].

Signal fading appears is produced by the signal bouncing off mountains and man-made structures as well as atmospheric and other interactions such as refraction and diffraction processes. The resultant received signal is modeled as a complex valued Gaussian process and is assumed to be comprised of a direct and many indirect components. When the impulse channel response is modeled as a zero mean, complex valued Gaussian process, its magnitude envelope at any time is Rayleigh distributed. In this case the channel is said to be a **Rayleigh fading channel**.

In the event that there are signal reflectors in the medium, the channel impulse response is no longer be modeled as having a zero mean. In this case, its magnitude envelope has a Rician distribution and the channel is said to be a **Rician fading channel**.

The probability density function (pdf) of a Rician faded signal is [Ref.8:pp.108]

$$f_A(a) = \frac{a}{2\sigma^2} \exp\left[-\frac{a^2 + \alpha^2}{2\sigma^2}\right] I_0\left(\frac{a\alpha}{\sigma^2}\right) u(a) \quad (1)$$

where $a > 0$, α^2 is the power in the direct component, $2\sigma^2$ is the power in the diffuse components, $I_0(a)$ is the zeroth-order modified Bessel function of the first kind, and $u(a)$ is the unit step function. For deep fading on the channel, the direct communication path is blocked, and as a consequence the direct signal component power is zero. In that event, the received signal is Rayleigh distributed, and its pdf is [Ref.6:pp.108]

$$f_A(a) = \frac{a}{\sigma^2} \exp\left[-\frac{a^2}{2\sigma^2}\right] u(a) \quad (2)$$

In this thesis, the channel model is assumed to be: 1) slow fading which implies the signal amplitude remains constant at least for the duration of a single hop, and 2) non-frequency selective which implies that the hop bandwidth is small compared to the coherence bandwidth. This implies that each hop frequency can be considered as if it were from an independent channel where the phase and amplitude are relatively constant.

D. BINARY RATIO-STATISTIC COMBINING RECEIVER.

Ratio-statistic combining implies that decision statistic for the receiver is a ratio. The general structure of the binary ratio-statistic combiner to be considered is depicted in Figures 1.3 and 1.4 [Ref.3:pp.26-28]. As illustrated, the incoming signal is dehopped and incoherently demodulated by a bandpass filter of bandwidth $B=R_h$ (where R_h is the hop rate) followed by an envelope or square-law detector for each of the two BFSK frequencies. The ratio-statistic for each detector output of a particular diversity reception is equal to the detector output divided by the value of the maximum detector output. Consequently, one detector output of the ratio-statistic receiver for a given diversity reception is always unity, and the other detector output for that diversity reception is less than unity [Ref.2:pp.146].

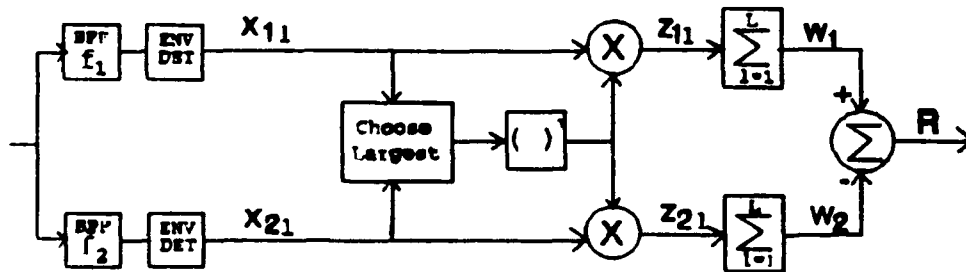


Figure 1.3 Diagram of Ratio Statistic Combiner.

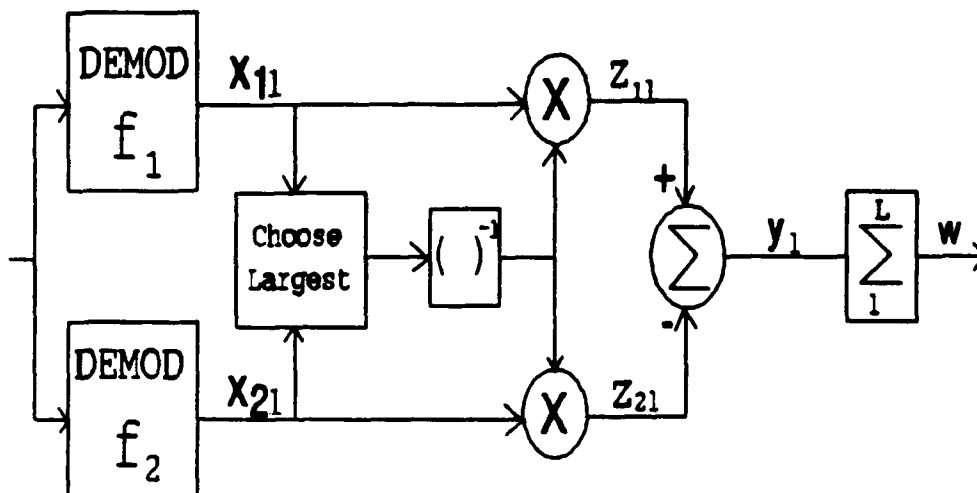


Figure 1.4 Alternate Implementation of the Ratio-Statistic combining receiver.

The mathematical analysis to develop the probability density function for $f_w(w)$ was performed by Riley [Ref.3:pp.27-53] where it is shown that Figure 1.3 is equivalent to Figure 1.4. Furthermore, it is shown that, in Figure 1.4, the random variable X_{1k} and X_{2k} are both normalized to obtain the random variable

$$Z_{ik} = \frac{X_{ik}}{q_k} \quad (3)$$

where $i = 1$ or 2 and $q_k = \max(X_{1k}, X_{2k})$. The random variable Z_k varies between 0 and 1 . The random variable Y_k varies from -1 to $+1$, and the random variable W varies from $-L$ to $+L$.

The probability of bit error P_{be} for a diversity L and a jamming duty factor γ is

$$P_{be} = \sum_{j=0}^L \binom{L}{j} \gamma^j (1-\gamma)^{L-j} P_{be}(j) \quad (4)$$

where $P_{be}(j)$ represents the conditional probability of bit error given that j of L hops are jammed. The number of hops that are jammed will depend on the duty factor of the jamming γ . The total probability of bit error is found by summing over all possible values of j . $P_{be}(j)$ is determined by

$$P_{be}(j) = \int_{-L}^0 f_w(w) dw \quad (5)$$

The derivation of the PDF for Y_k and W requires consideration of two cases: when the partial-band interference is present and when it is not. The evaluation of $f_w(w)$ requires an L fold convolution. The noise power at the receiver when partial-band interference is present with probability γ is given by

$$\sigma_k^2 = (\gamma^{-1} N_j + N_o) B \quad (6)$$

The noise power at the receiver when no partial-band interference is present with probability $1-\gamma$ is

$$\sigma_k^2 = N_o B \quad (7)$$

The pdf for the random variable Y_k is obtained as follows. The dehopped signal is expressed as

$$S(t) = \sqrt{2}a \cos(\omega t + \theta) \quad (8)$$

where ω is the frequency of the dehopped signal, θ is the phase, $(2)^{1/2}a$ is the amplitude, and $0 \leq t \leq T_b$.

If the signal is assumed to be in the upper branch of the receiver, then $f_{X_{1k}}$ is Rician distributed and is conditional on a being present. The pdf $f_{X_{2k}}$ of X_{2k} in the lower branch is Rayleigh distributed.

The random variables X_{ik} are independent, and the joint density function $f_{X_{1k}X_{2k}}(X_{1k}X_{2k}|a)$ is obtained as the product of $f_{X_{1k}}$ and $f_{X_{2k}}$. Next, appropriate auxiliary variables are defined, and the Jacobian of the transformation is obtained. Finally, the conditional pdf $f_{Y_k}(Y_k|a)$ of Y_k is obtained by integrating over the auxiliary variable.

The unconditional pdf for Y_k is

$$f_{Yk}(y_k) = \int_0^{\infty} f_{Yk}(Y_k|a) f_A(a) da \quad (9)$$

where $f_A(a)$ represents the pdf of the signal amplitude, which is a Rician random variable as given in equation (2). The diffuse signal-to-noise ratio is defined as

$$\xi_k = \frac{2\sigma^2}{\sigma_k^2} \quad (10)$$

The direct signal to noise ratio is defined as

$$\rho_k = \frac{\alpha^2}{\sigma_k^2} \quad (11)$$

and the direct to diffuse ratio as

$$DDR = \frac{\alpha^2}{2\sigma^2} \quad (12)$$

The PDF for the random variable W as $f_w(w)$ is numerically evaluated from

$$f_w(W) = [f_{Yk}^j(Y_k)]^{\otimes j} \otimes [f_{Yk}^o(Y_k)]^{\otimes (L-j)} \quad (13)$$

where the j superscript implies jammed hops and the o superscript implies unjammed hops.

$P_{be}(j)$ is obtained by equation (5), and the probability of bit error is found by numerically evaluating equation (4).

1. Unconditional pdf $f_{Y_k}(Y_k)$ for envelope detection

The conditional pdf for the random variable X_{1k} is given by

$$f_{X_{1k}}(X_{1k}|a) = \frac{X_{1k}}{\sigma_k^2} e^{-\frac{(X_{1k}^2 + 2a^2)}{2\sigma_k^2}} I_0\left(\frac{\sqrt{2}aX_{1k}}{\sigma^2}\right) \quad (14)$$

The pdf for the variable X_{2k} is

$$f_{X_{2k}}(X_{2k}) = \frac{X_{2k}}{\sigma_k^2} e^{-\frac{X_{2k}^2}{2\sigma_k^2}} \quad (15)$$

The probability density function for the random variable Y_k in the interval of $-1 \leq Y_k \leq 0$ is given by

$$f_{YK}(Y_K) = \frac{2(1+Y_K)}{[1+(1+Y_K)^2][1+\xi_K+(1+Y_K)^2]} e^{-\frac{\rho_K}{1+\xi_K+(1+Y_K)^2}} \times \left[1 + \frac{(1+Y_K)^2}{1+\xi_K+(1+Y_K)^2} \left(\xi_K + \frac{\rho_K(1+(1+Y_K)^2)}{1+\xi_K+(1+Y_K)^2} \right) \right] \quad (16)$$

and for $0 \leq Y_K \leq 1$

$$f_{YK}(Y_K) = \frac{2(1-Y_K)}{[1+(1-Y_K)^2][1+(\xi_K+1)(1-Y_K)^2]} e^{-\frac{\rho_K(1-Y_K)^2}{1+(\xi_K+1)(1-Y_K)^2}} \times \left[1 + \frac{1}{1+(\xi_K+1)(1-Y_K)^2} \left(\xi_K + \frac{\rho_K(1+(1-Y_K)^2)}{1+(\xi_K+1)(1-Y_K)^2} \right) \right] \quad (17)$$

2. Unconditional pdf $f_{YK}(Y_K)$ for square law detection.

The conditional pdf for the random variable X_{1k} is given by

$$f_{X1k}(X_{1k}|a) = \frac{1}{\sigma_k^2} e^{-\frac{(X_{1k}^2 + 2a^2)}{2\sigma_k^2}} I_0\left(\frac{\sqrt{2}aX_{1k}}{\sigma^2}\right) \quad (18)$$

The pdf for the random variable X_{2k} is

$$f_{X2k}(X_{2k}) = \frac{1}{\sigma_k^2} e^{-\frac{X_{2k}^2}{2\sigma_k^2}} \quad (19)$$

The probability density functions for the random variable Y_k in the interval $1 \leq Y_k \leq 0$ is given by

$$f_{Y_k}(Y_k) = \frac{1}{(2+Y_k)(2+\xi_k+Y_k)} e^{-\frac{\rho_k}{2+\xi_k+Y_k}} \times \left[1 + \frac{(1+Y_k)}{2+\xi_k+Y_k} \left(\xi_k + \frac{\rho_k(2+Y_k)}{2+\xi_k+Y_k} \right) \right] \quad (20)$$

and for $0 \leq Y_k \leq 1$

$$f_{Y_k}(Y_k) = \frac{1}{(2-Y_k)[2-Y_k+\xi_k(1-Y_k)]} e^{-\frac{\rho_k(1-Y_k)}{2-Y_k+\xi_k(1-Y_k)}} \times \left[1 + \frac{1}{2-Y_k+\xi_k(1-Y_k)} \left(\xi_k + \frac{\rho_k(2-Y_k)}{2-Y_k+\xi_k(1-Y_k)} \right) \right] \quad (21)$$

E. FORWARD ERROR CORRECTION CODING.

Forward error correction (FEC) is a method that employs the adding of systematic redundancy and noise averaging at the transmit end of a link such that errors caused by the channel can be corrected at the receiver by means of a decoding algorithm. The binary data source generates information bits at R_i seconds. These information bits are encoded at a coded rate R , and the coded bit energy is

$$E_c = R E_b \quad (22)$$

The encoder output sequence is modulated and transmitted over the communication channel. At the receiver, the demodulator output is passed through a decoder to recover the original binary data.

FEC can be implemented with either block or convolutional codes [Ref.7:pp.417-441]. Convolutional codes are selected for this thesis.

A. J. Viterbi [Ref.8] defines a convolutional encoder as a linear finite state machine consisting of a K -stage shift register and n linear algebraic function generators. The binary input data is shifted along the register b bits at a time.

Each coded symbol carries an average of b/n information bits, and the code rate R is

$$R = \frac{b}{n} \quad (23)$$

Figure 1.5 depicts the general structure of a convolutional encoder, where for a given information bit rate the required E_b/N_0 for a specific bit error rate with FEC is generally less than the E_b/N_0 required without FEC. Coding gain is defined as the difference in E_b/N_0 with and without FEC [Ref.7:pp.419].

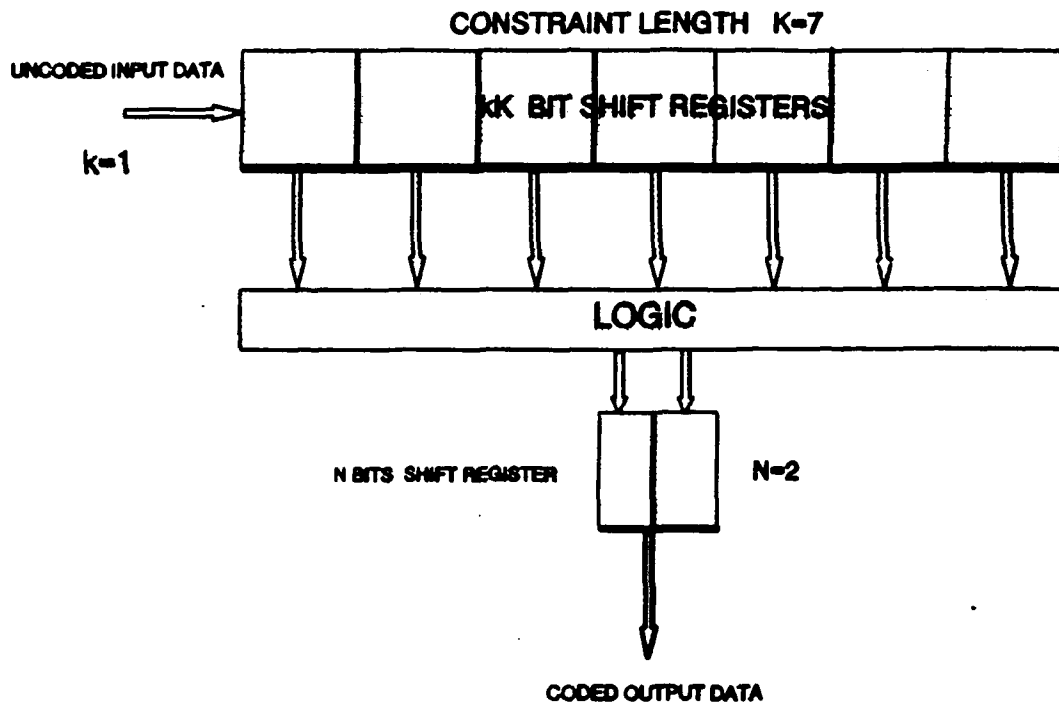


Figure 1.5 A Convolutional Encoder.

The Viterbi decoder is one of the most common decoders for convolutional codes because it is the optimum decoding algorithm in the sense of maximum likelihood decoding of the entire sequence for convolutional codes. The Viterbi decoder performance can be approximated through the use of an upper bound [Ref.9:pp.407]. For the rate of $1/2$, constraint length

K=7 convolutional code, the decoded bit error probability is bounded by

$$P_{dbe} \leq \frac{1}{2} (36D^{10} + 211D^{12} + 1404D^{16} + 11633D^{18} + \dots) \quad (24)$$

where

$$D = 2\sqrt{P_{be}(1-P_{be})} \quad (25)$$

III. METHOD OF RESEARCH

Computation of the probability of bit error involves a numerical evaluation of (12), (33), and (34). Numerical evaluations are done for both envelope and square-law detection.

The coded system performance is shown by plotting the decoded bit error probability P_{dbe} versus the average signal bit energy density-to-jamming noise power spectral density ratio E_b/N_j . Several constraints are established in order to analyze the performance of the communication system.

The jamming duty factor γ takes the values .001, .05, .25, and 1.0 to determine the effects of different amounts of partial-band interference on the system. The direct-to-diffuse ratio DDR takes the values .01, 10, and 10000 to determine the effects of Rayleigh, Rician, and Gaussian channels on the system. The bit energy-to-noise ratio E_b/N_0 takes the values 13.35 and 16.00 dB to evaluate the effects of thermal noise on the system. The bit energy-to-jammer density ratio E_b/N_j takes values from 0 to 40 dB to review the effects of jamming against the system and each constraint is evaluated for diversity L values from 1 to 4.

The uncoded and coded performances are compared in order to determine the advantages of using FEC with the spread

spectrum frequency hopping/noncoherent binary FSK ratio-
statistic combining receiver in a communication channel
characterized by fading and partial-band interference.

IV. DISCUSSION OF RESULTS

The channel is modeled for a moderately strong direct-to-diffuse signal ratio $\alpha_k^2/2\sigma^2=10$ which is considered Rician, for $\alpha_k^2/2\sigma^2=.01$ which is considered a Rayleigh faded channel, and Gaussian with $\alpha_k^2/2\sigma^2=10000$. The worst jamming case corresponds to broadband jamming $\gamma=1$.

Performance with FEC in all cases showed an appreciable improvement in performance as expected. Comparison of the rate 1/2 convolutional code versus uncoded performance shows the expected coding gain. The coding gain is based on an optimum diversity level, this being the level where the probability bit error approaches an asymptotic lower limit for a specific value of bit energy-to-noise density ratio. Uncoded performance showed an asymptotic lower limit of $P_{be}=10^{-4}$ for a bit energy-to-noise of 16 dB and $P_{be}=10^{-3}$ for 13.35 dB; however, decoded performances show an asymptotic lower limit of $P_{be}=10^{-9}$ for a bit energy-to-noise density ratio of 16 db and $P_{be}=10^{-6}$ for 13.35 dB. The worst case occurs at the point where the probability of the bit error reaches its maximum.

Figures 3.1 to 3.4 are the envelope receiver performance for partial-band and broadband jamming at a direct-to-diffuse ratio of 10 for diversities $L=1, 2, 3$ and 4. Figure 3.1 shows that for bit energy-to-jamming density ratios greater than 10

dB, the performance with broadband jamming is better than 25% partial-band interference. For bit energy-to-jamming ratios greater than 15 dB, again, the performance with broadband jamming is better than both 5% and 25% partial-band interference. The uncoded system shows performance degradation due partial-band interference from 8 to 40 dB, while the coded system shows better performance against partial-band interference from 15 to 40 dB. For bit energy-to-jamming density ratios less than 15 dB, receiver performance improves more for partial-band than broadband jamming.

Figures 3.2, 3.3, and 3.4 show that degradation due to partial-band jamming is reduced dramatically for $L=2, 3$, and 4. Figure 3.5 shows the worst case for diversities of $L=1, 3$, and 4. It is interesting to note that if we compare the plots for diversities of $L=1$ and 4, the better performance corresponds to diversity $L=4$, but between $L=3$ and 4, diversity $L=3$ performs better than $L=4$. There are improvements in performance when diversity $L=3$ is used for bit energy-to-jamming density ratios above 18 dB.

Figure 3.6 is the receiver performance in the presence of a Gaussian channel which is degraded significantly for no diversity while Figure 3.7 shows how this degradation is reduced when diversity is increased.

Figure 3.8, for a Gaussian channel, we see that the performance advantage due to increased diversity is lost for bit energy-to-jamming density ratios greater than 26 dB, where

the $L=1$ worst case performance drops below the $L=4$ worst case performance.

Figures 3.9 and 3.10 show the receiver performance for a Rayleigh channel; the worst case performance corresponds to broadband jamming and the effects of increasing diversity are an important consideration.

Figure 3.11 shows, for different amounts of channel fading, the receiver performance with 5% partial-band interference and diversity $L=4$. Figure 3.12 illustrates the effects of broadband jamming. The worst case performance for Rayleigh channels corresponds to broadband jamming.

For $E_b/N_0=13.35$ dB, Figures 3.13, 3.14, 3.15, and 3.16 show receiver performance for different fractions of partial-band and broadband jamming in the presence of a Rician faded channel for diversities of $L=1, 2, 3$ and 4. For no diversity, the performance with broadband jamming is better than 5% partial-band interference for bit energy-to-jamming density ratios from 17 to 30 dB and better than 25% partial-band interference for bit energy-to-jamming density ratios lower than 30 dB. Partial-band interference degrades the receiver performance dramatically versus the receiver performance for bit energy-to-noise of 16 dB. When diversity is increased, degradation is reduced for diversity $L=2$ and worst case performance occurs for broadband jamming; however, diversity greater than $L=2$ does not improve performance because

diversity $L=2$ has an asymptotic lower limit of $P_{be}=10^{-5}$ while for $L=4$ the asymptotic lower limit is $P_{be}=10^{-4}$.

Figure 3.17 shows worst case performance for diversities $L=1, 3$, and 4 . The advantage of using diversity is lost for low values of bit energy-to-noise density ratios.

Figure 3.18 shows receiver performance for a Gaussian channel, which is better than that for a Rician faded channel (cf., Figure 3.16).

For Gaussian channels, Figure 3.19 shows that performance with increased diversity is dramatically poorer for all bit energy-to-jamming density ratios.

Figure 3.20 shows both bit energy-to-noise density ratios for Rician faded channels for 13.35 and 16 dB. For larger values of energy-to-jamming density ratios, receiver performance tends to be controlled by thermal noise.

Receiver performance for $L=3$ is better than $L=1$ for a bit energy-to-noise density ratio of 16 dB for all bit energy-to-jamming density ratios above 17 dB. For a bit energy-to-noise density ratio of 13.35 dB, lower orders of diversity perform better than higher for all values of bit energy-to-jamming density ratios.

In Figures 3.21, 3.22, and 3.23, the performance of the square-law receiver is illustrated for a bit energy-to noise ratio of 16 dB and diversities of $L=1, 3$ and 4 for a Rician

channel. For diversities greater than $L=1$, the worst case performance tends to be when the interference is broadband. For the envelope detection case no performance improvement is obtained for diversities greater than $L=3$. Figure 3.24 and Figure 3.25 show worst case performance for diversities of $L=1$, 3, and 4 for bit energy-to-noise density ratios of 16 dB and 13.35 dB, respectively.

Figures 3.26 and 3.27 show comparisons between both coded detections examined for bit energy-to-noise density ratios of 13.35 and 16 dB. For diversities of $L=1$ and $L=3$, the envelope detector performs better than the square-law detector for all values of bit energy-to-jamming density ratios. For uncoded detection, the envelope detector performs better than square-law detector for diversities of $L=3$ or 4.

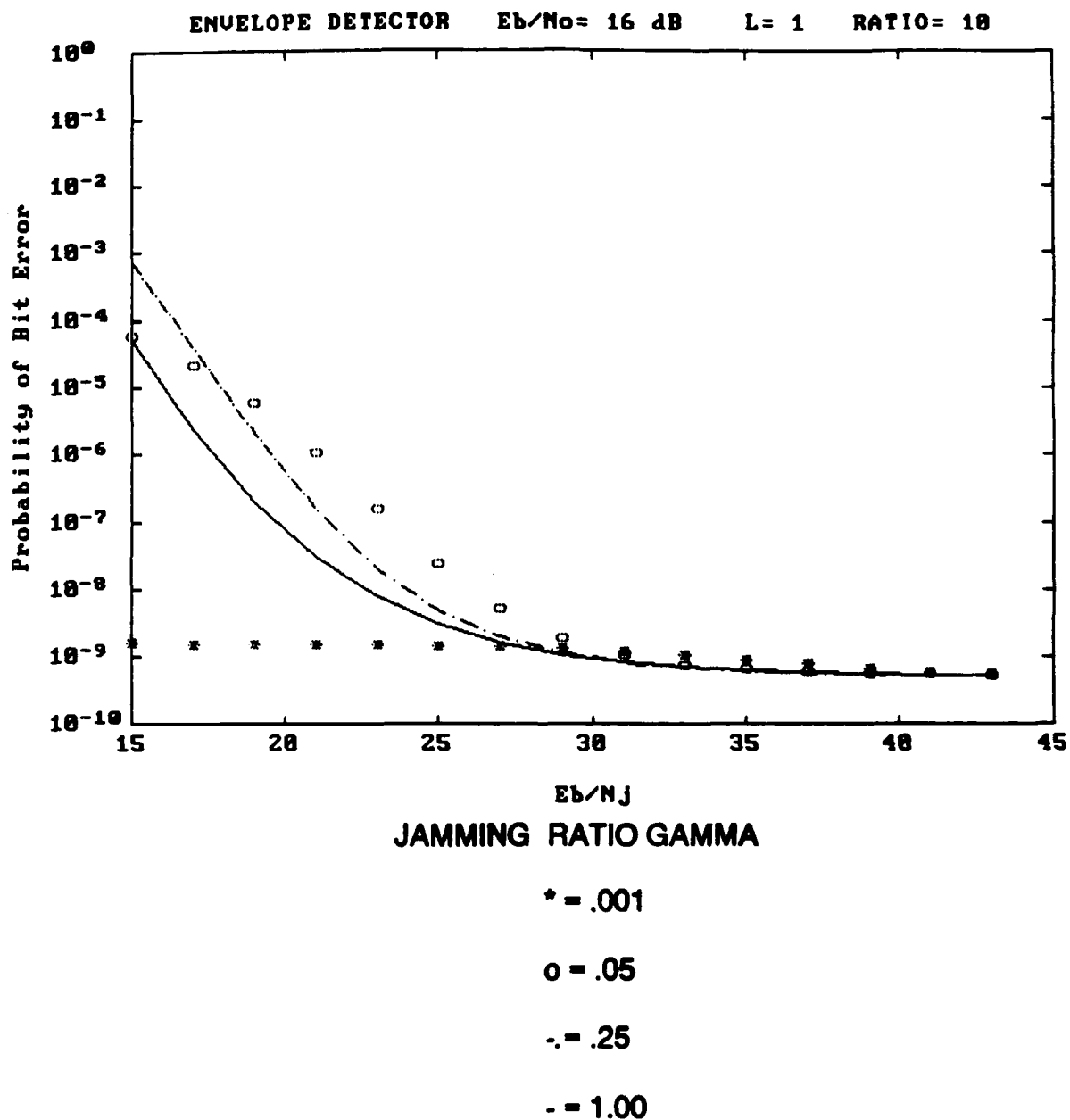


Figure 3.1. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 16$ dB, Direct to Diffuse RATIO=10, and $L=1$.

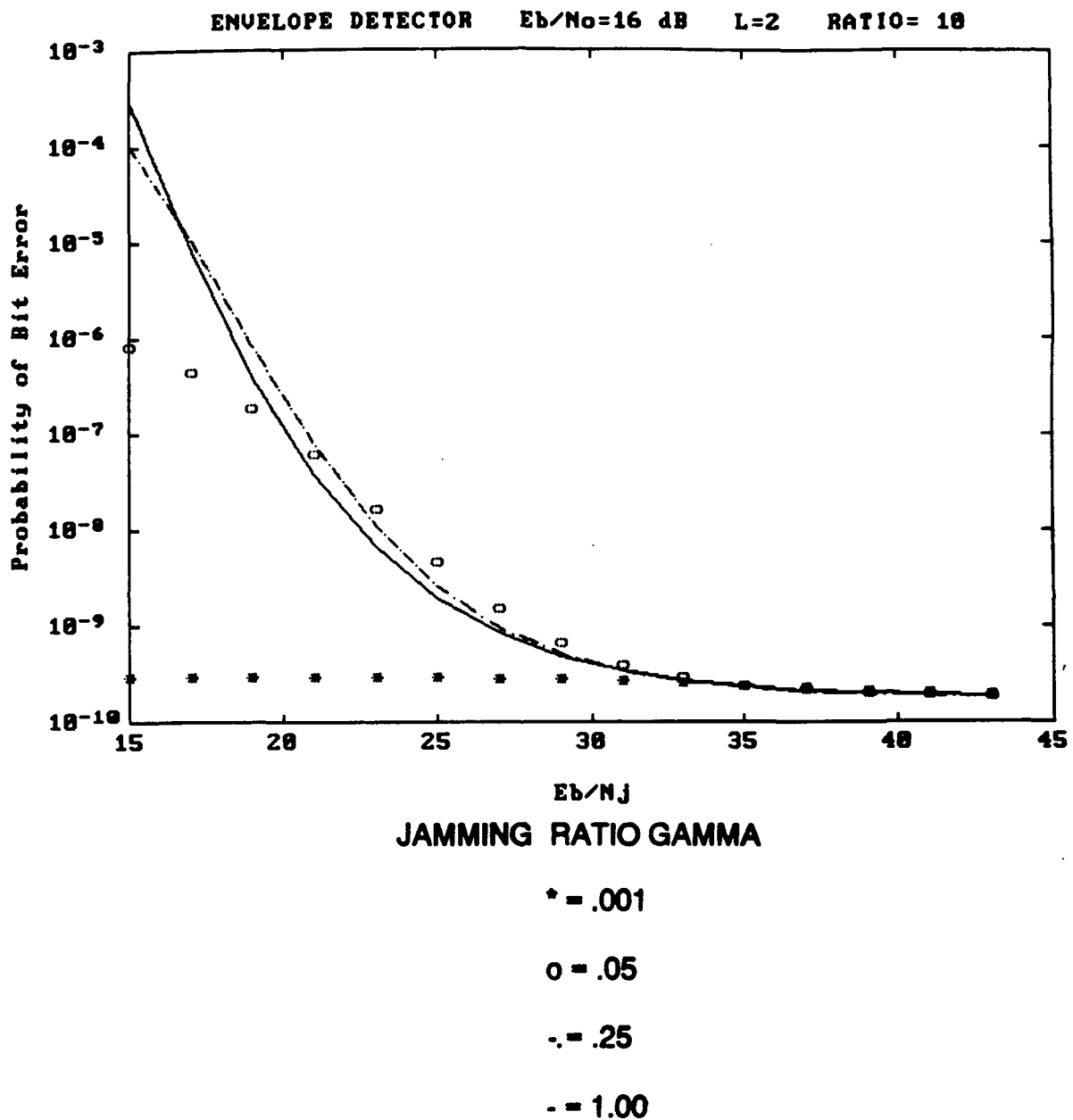


Figure 3.2. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10, and $L=2$.

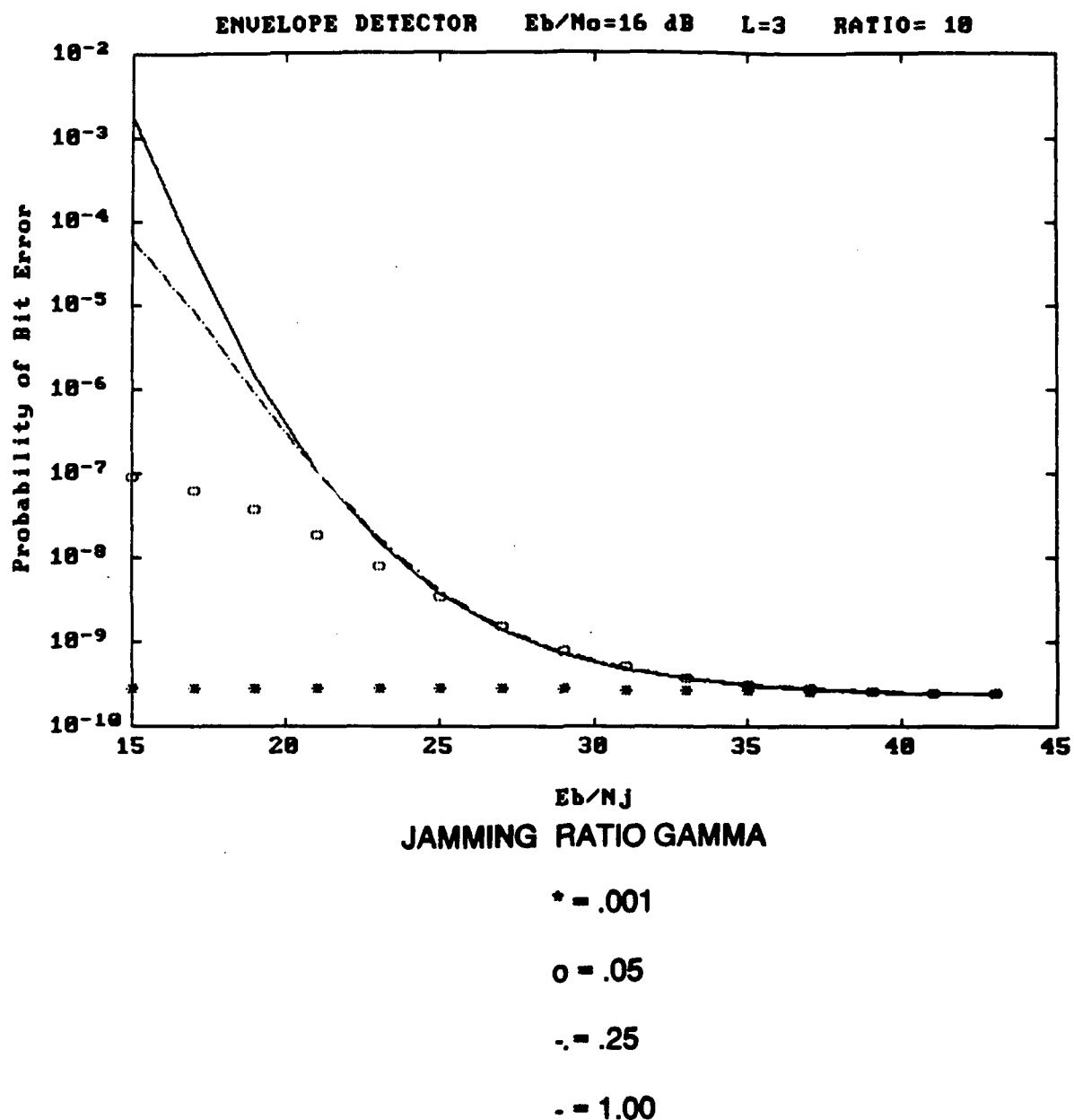


Figure 3.3. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10, and $L=3$.

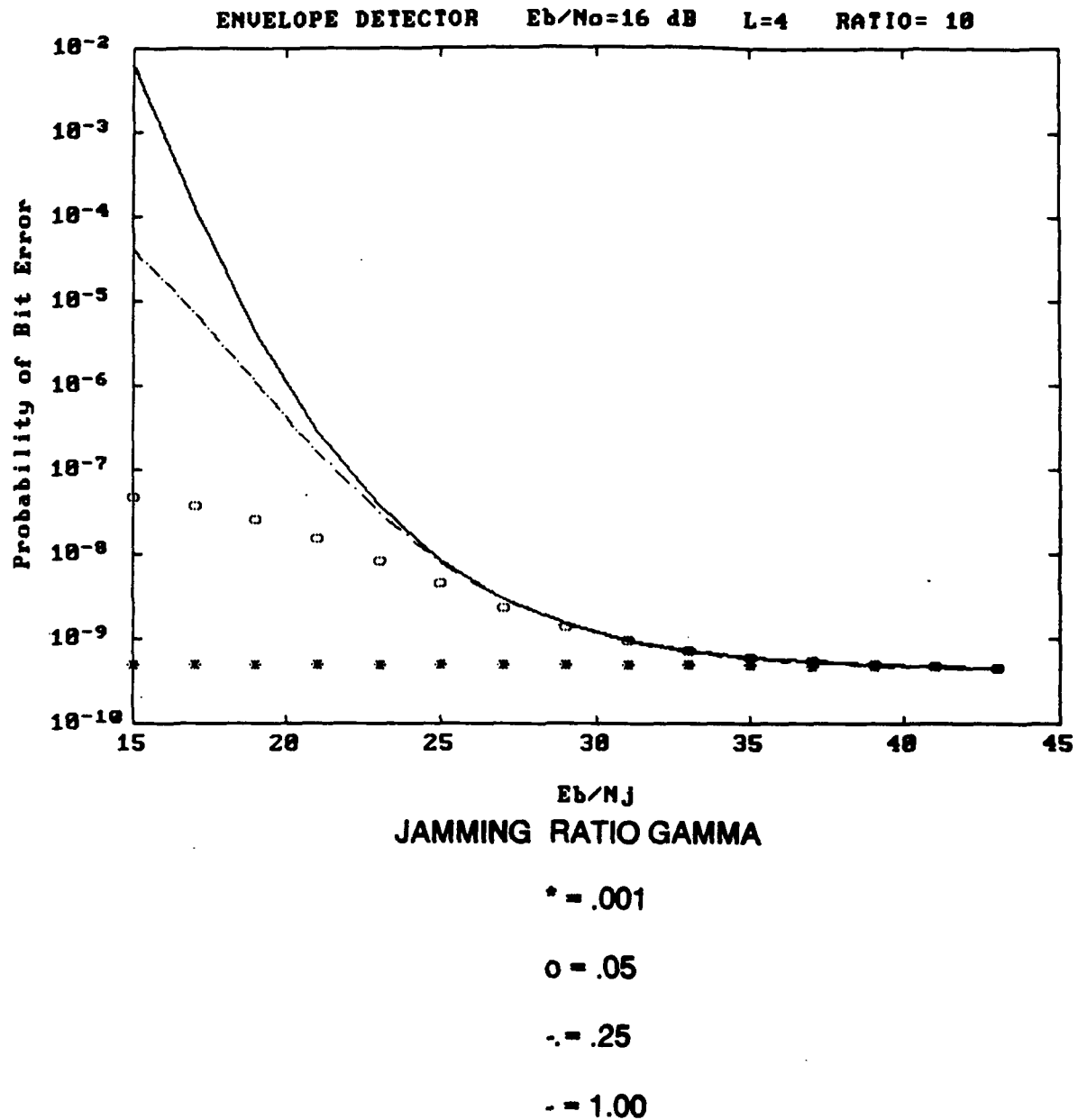


Figure 3.4. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10, and $L=4$.

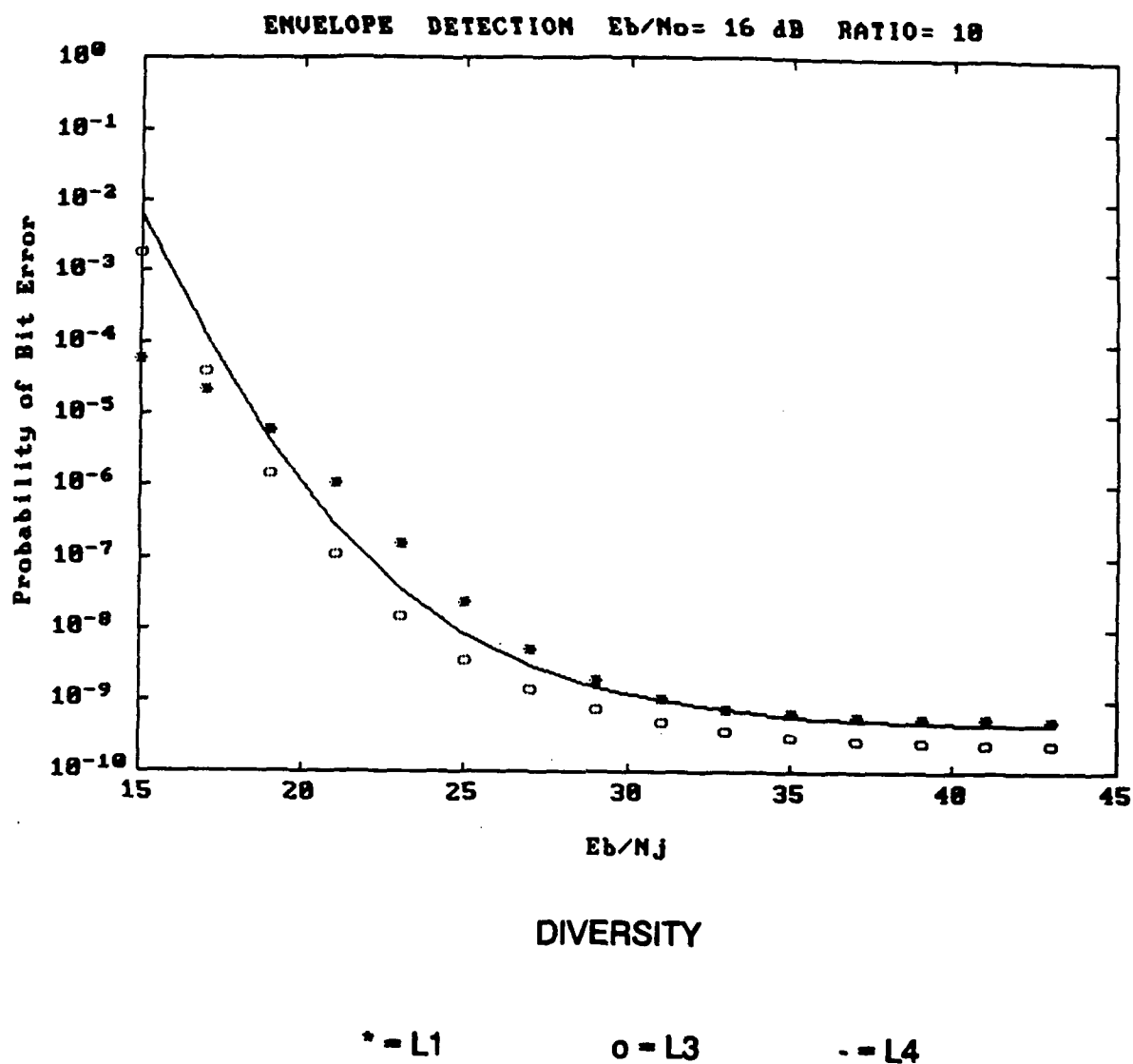


Figure 3.5. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 16$ dB, Direct to Diffuse RATIO=10, and the worst case for $L=1, 3$ and 4 .

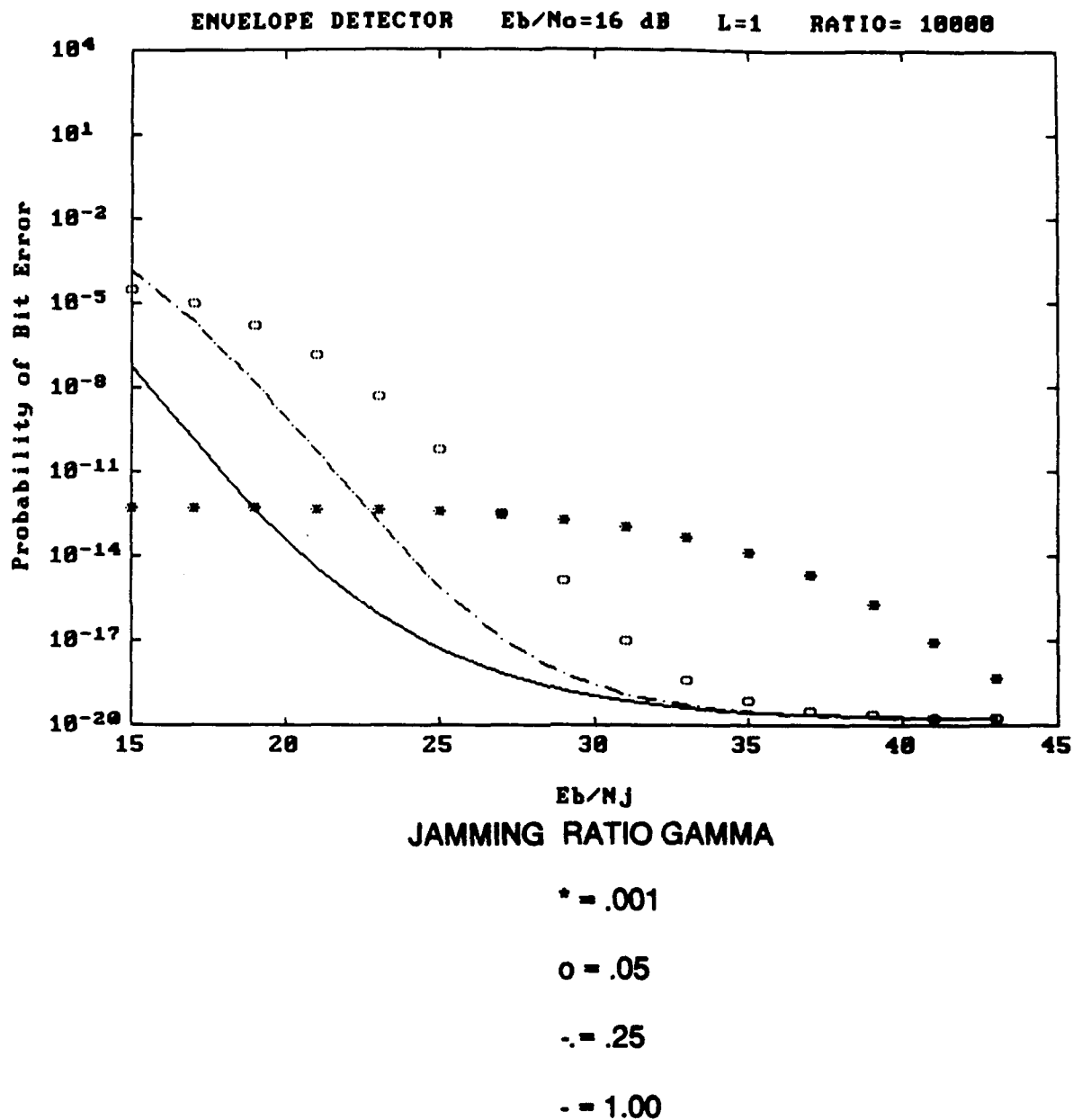


Figure 3.6. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10000, and $L=1$.

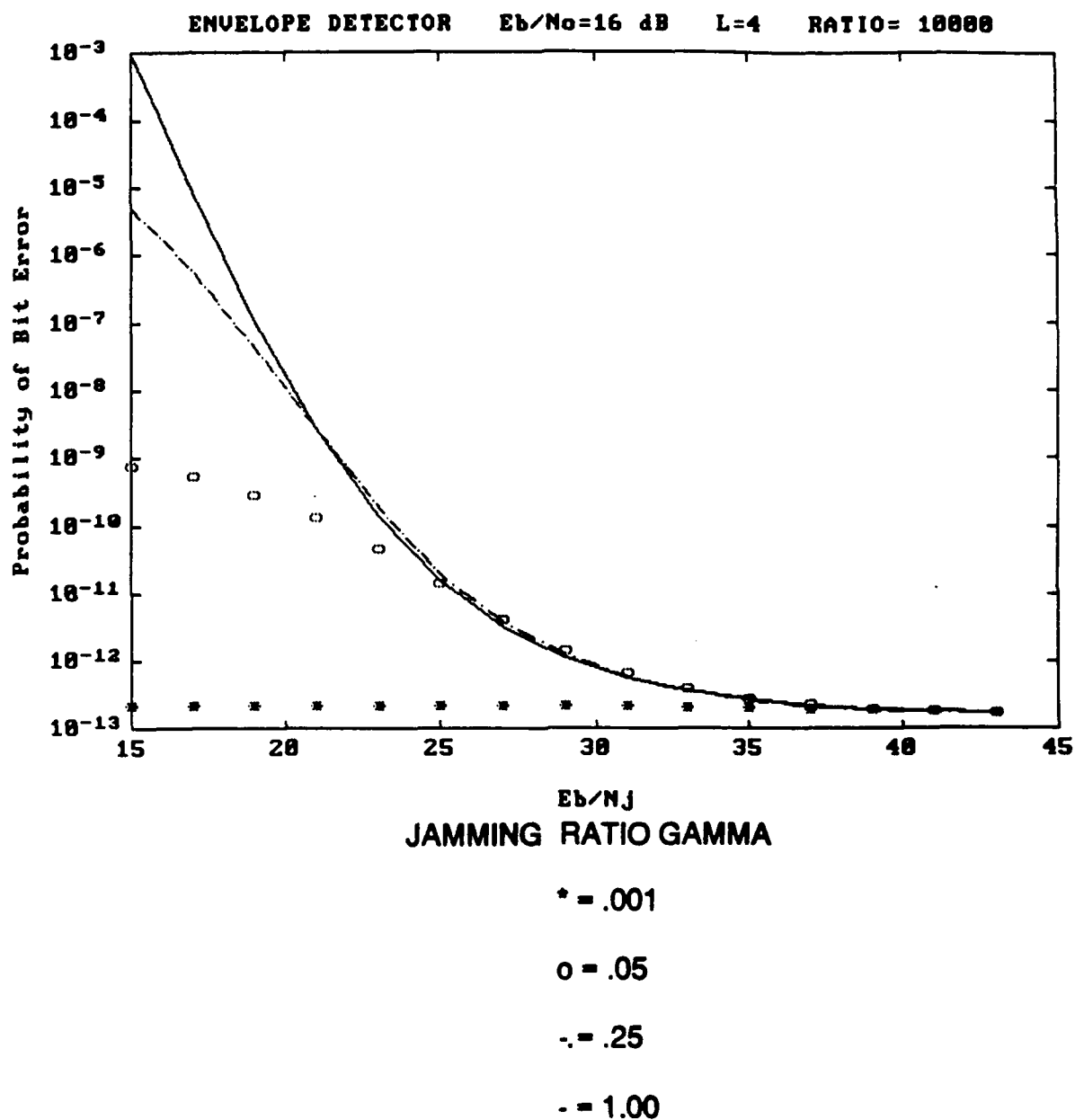


Figure 3.7. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10000, and $L=4$.

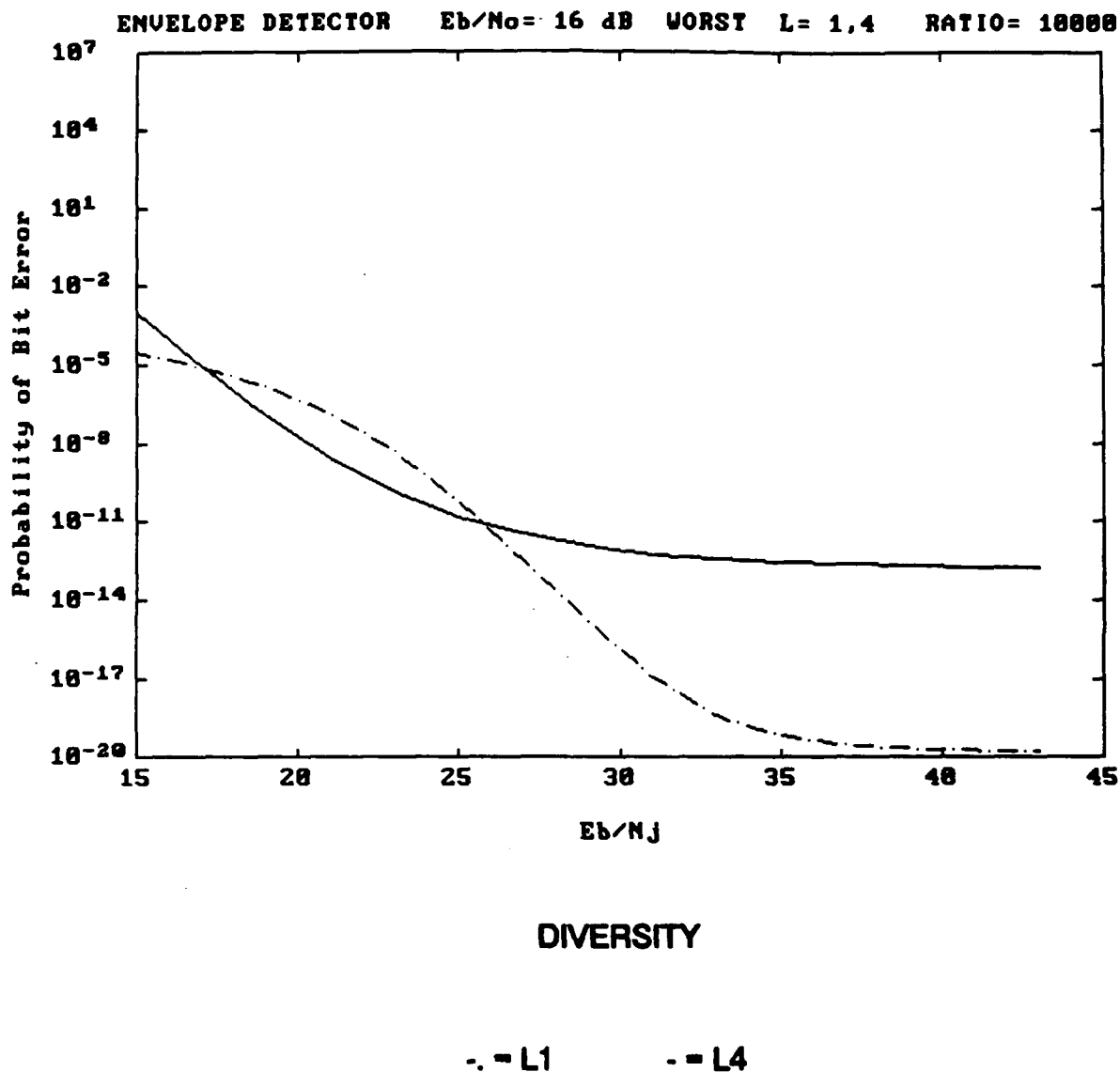
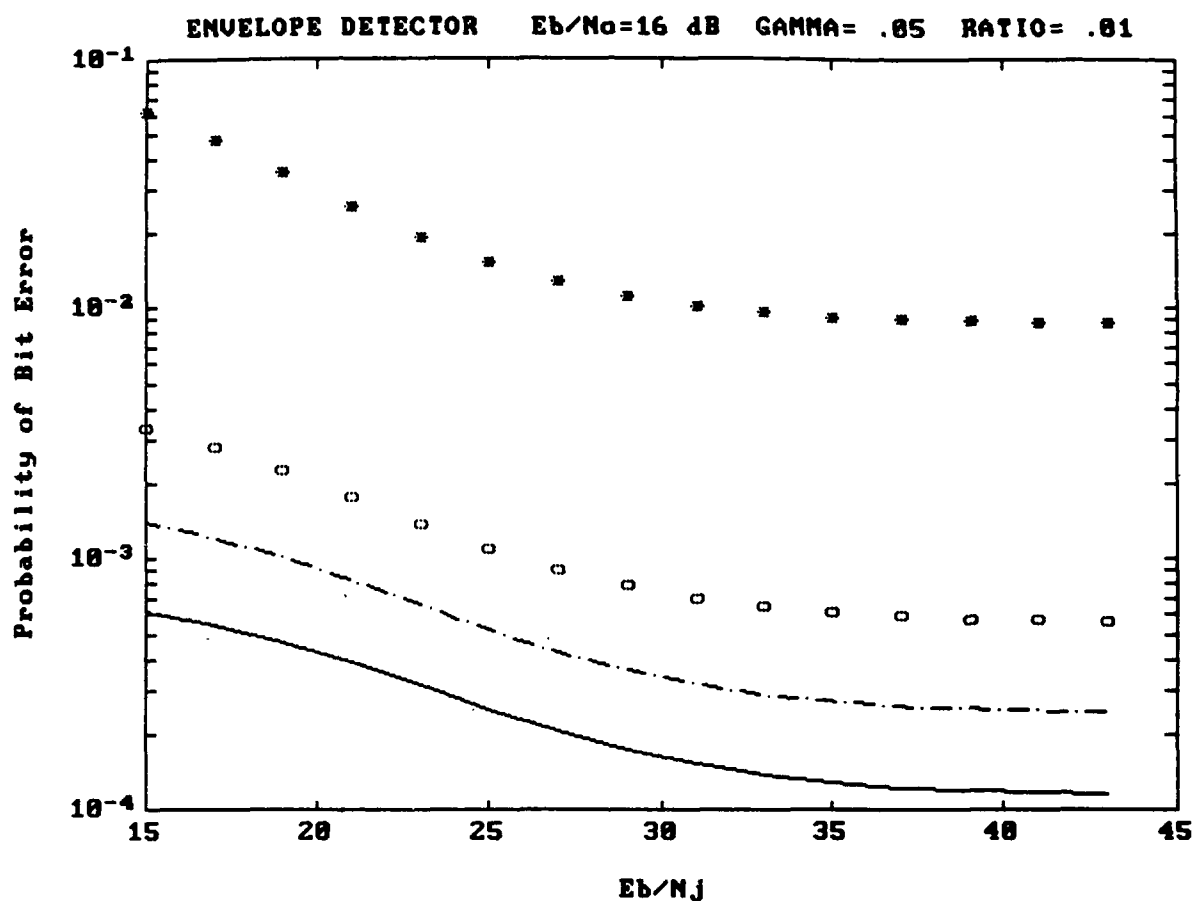


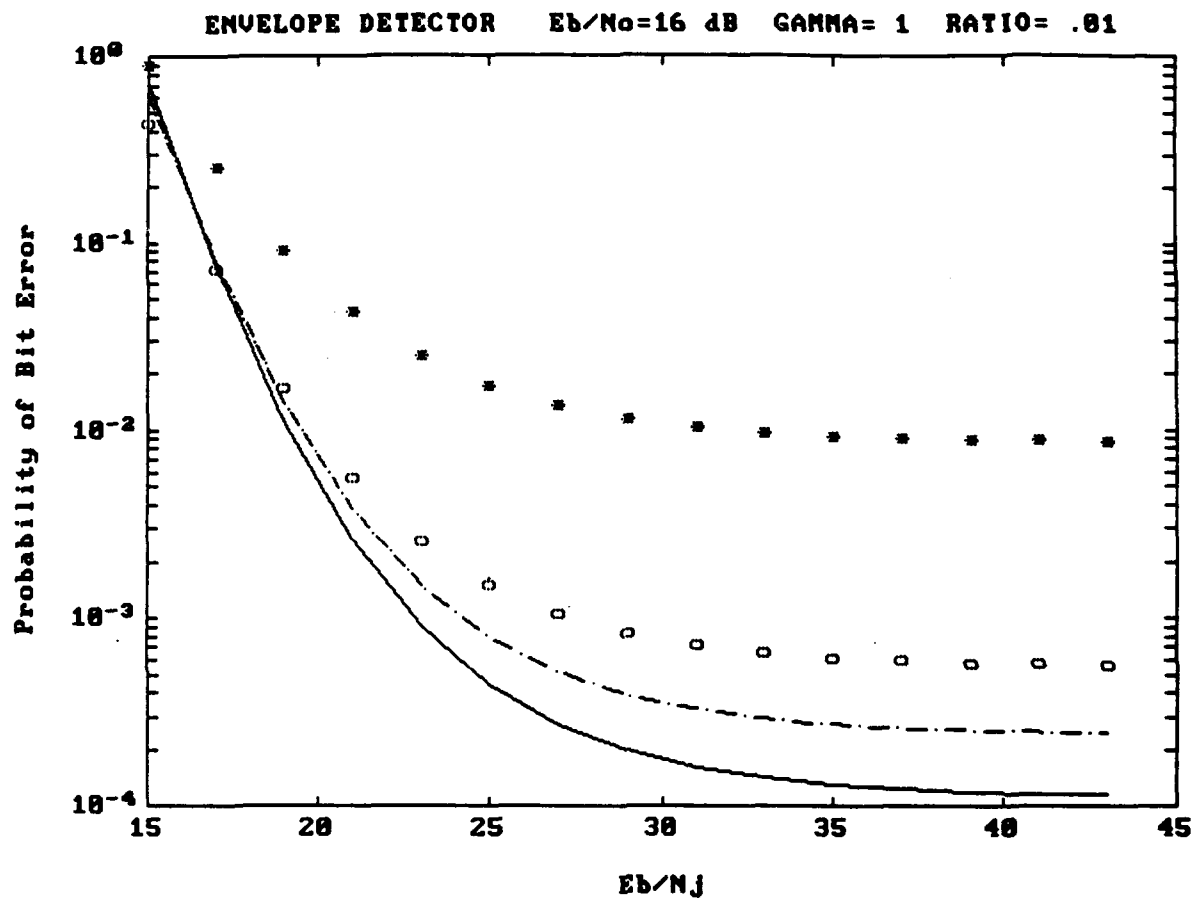
Figure 3.8. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 16$ dB, Direct to Diffuse RATIO=10000, and Worst $L=1$ and 4.



DIVERSITY

* = L1 o = L2 - . = L3 - = L4

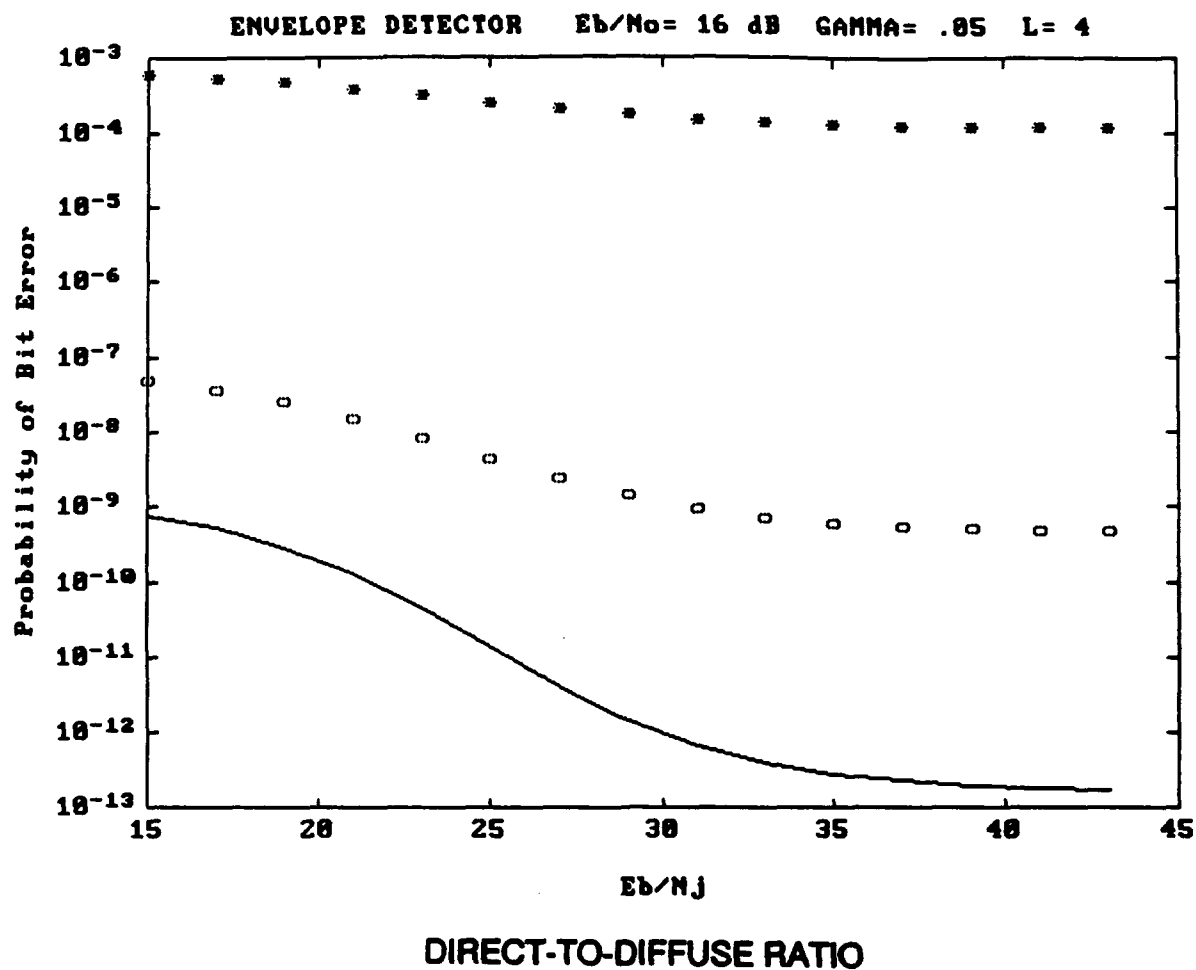
Figure 3.9. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0=16$ dB, Direct to Diffuse $\text{RATIO}=.01$, $\text{GAMMA}=.05$, and $L=1,2,3$ and 4.



DIVERSITY

* = L1 o = L2 - - = L3 - . = L4

Figure 3.10. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0=16$ dB, Direct to Diffuse $\text{RATIO}=.01$, $\text{GAMMA}=1$, and $L=1,2,3$ and 4.



* = .01 o = 10 - = 10000

Figure 3.11. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 16$ dB, Different Amounts of Fading, $\text{GAMMA} = .05$, and $L = 4$.

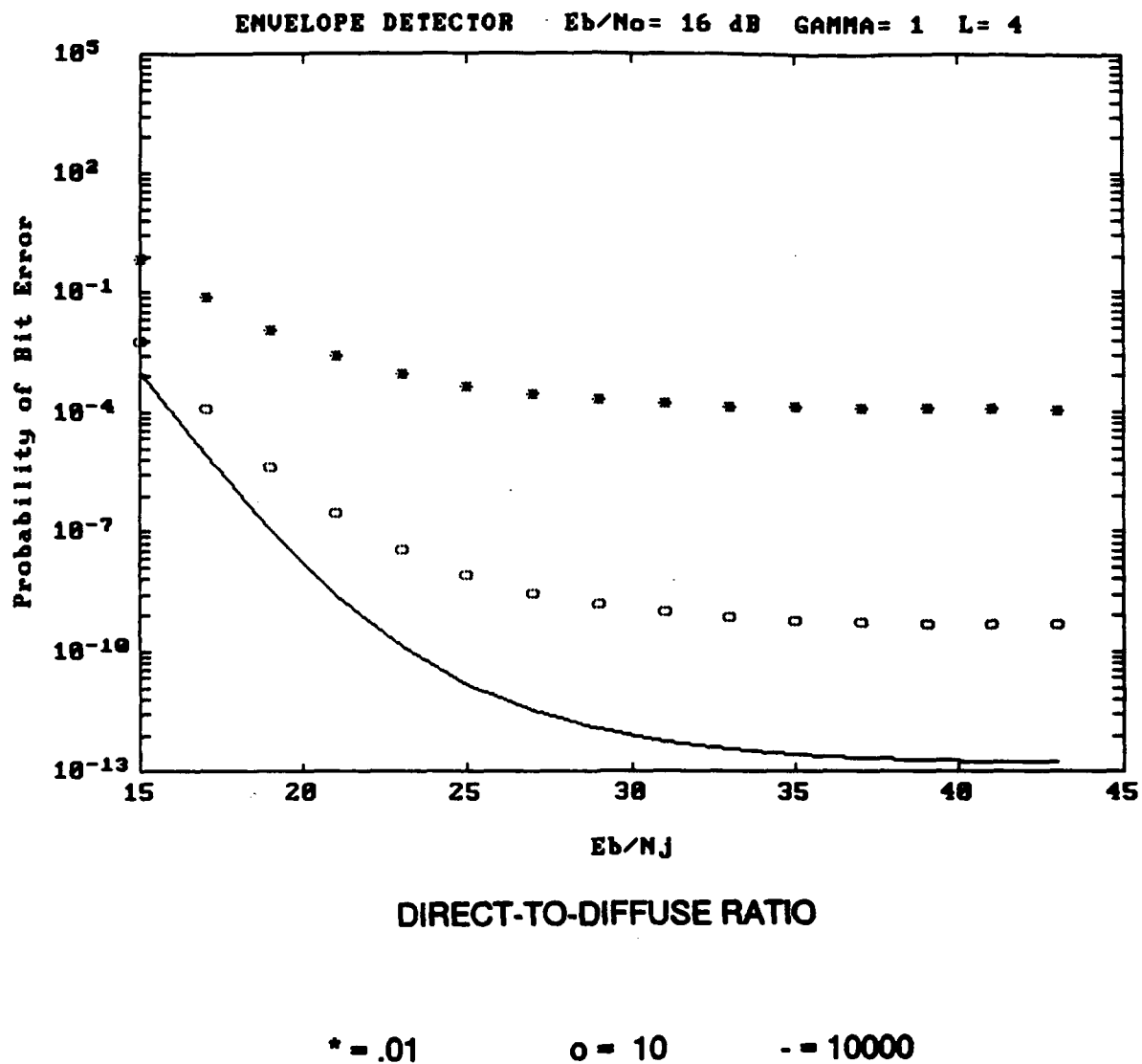


Figure 3.12. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 16$ dB, Different Amounts of Fading, $\text{GAMMA} = 1$, and $L = 4$.

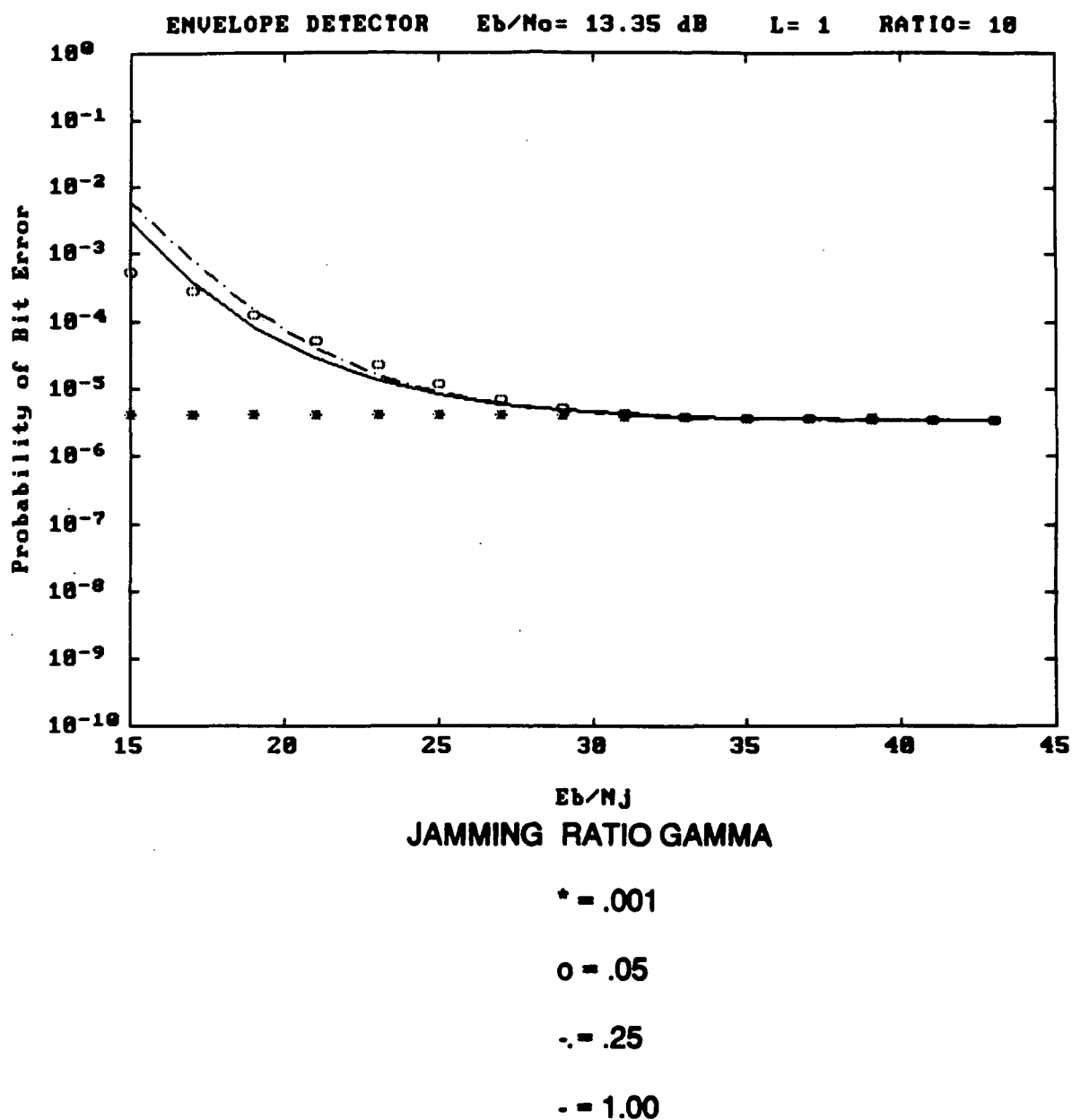


Figure 3.13. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10, and $L=1$.

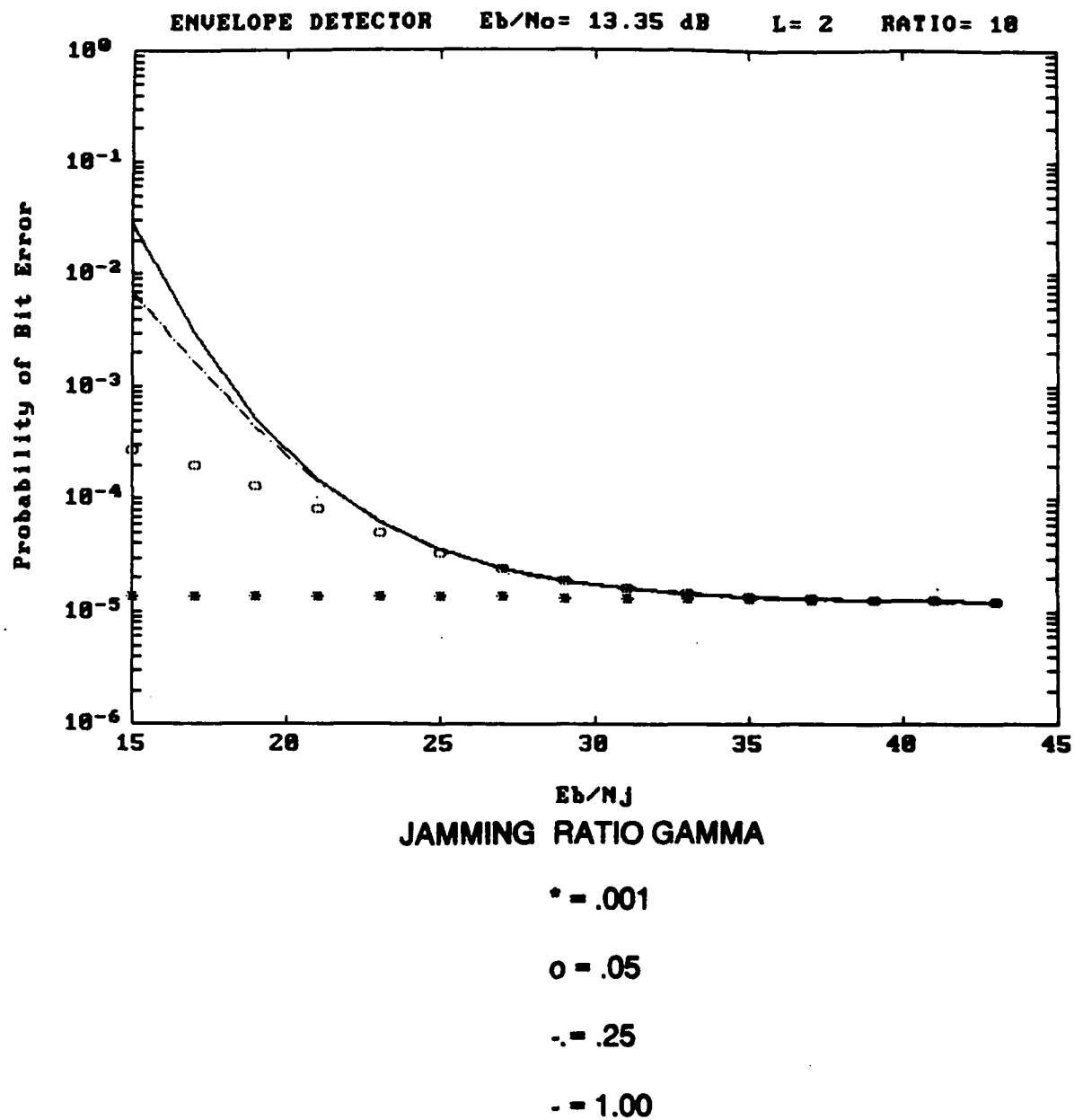
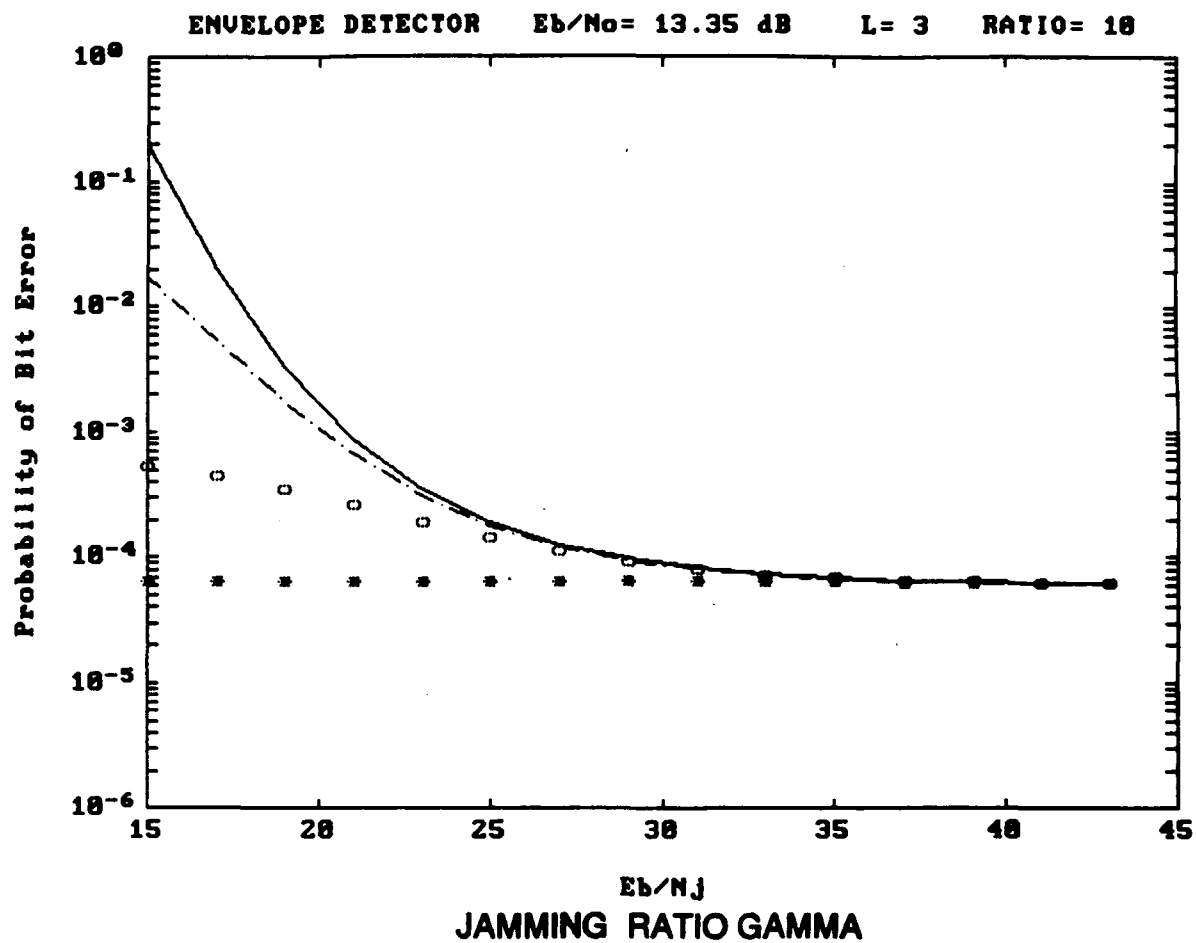


Figure 3.14. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10, and $L=2$.



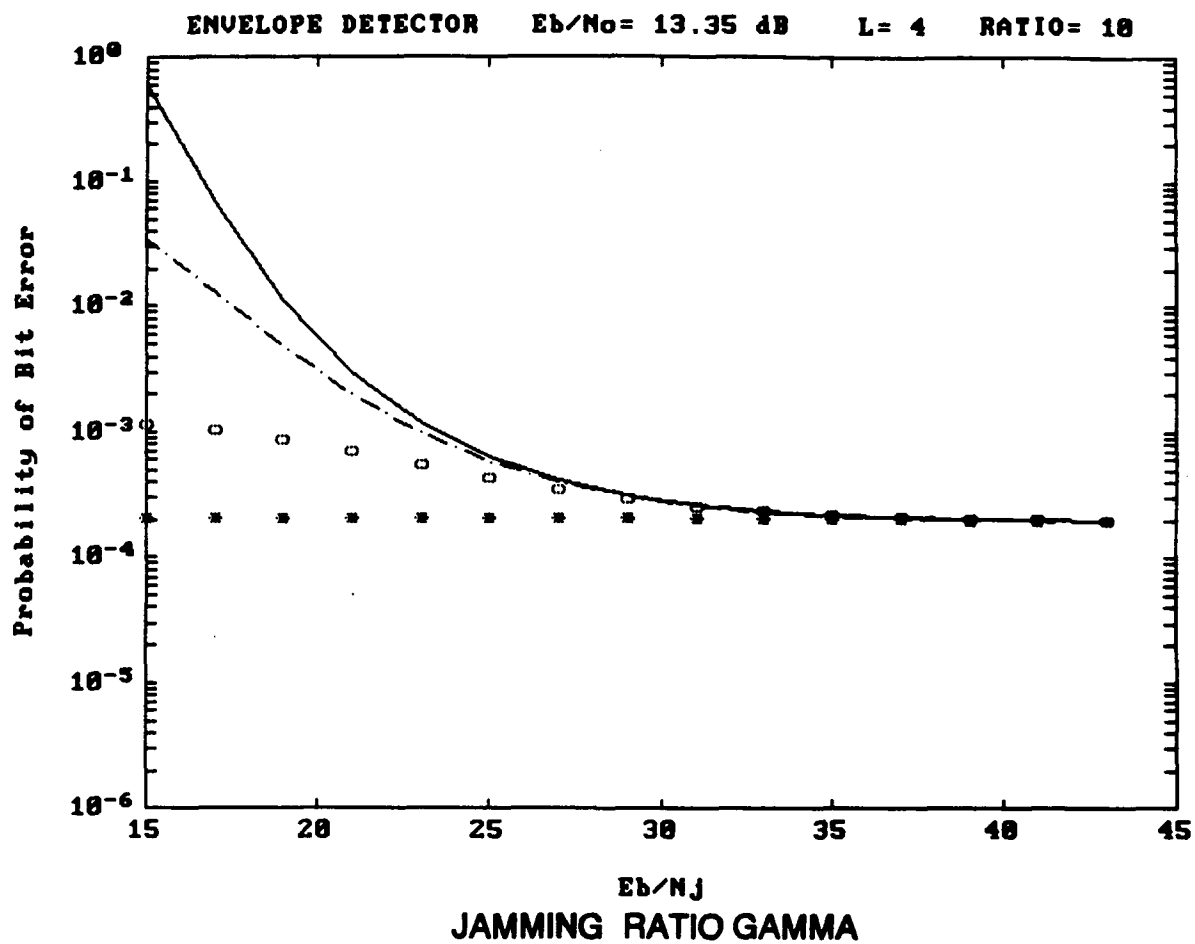
* = .001

o = .05

.. = .25

- . = 1.00

Figure 3.15. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10, and $L=3$.



* = .001

o = .05

.- = .25

- = 1.00

Figure 3.16. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10, and $L=4$.

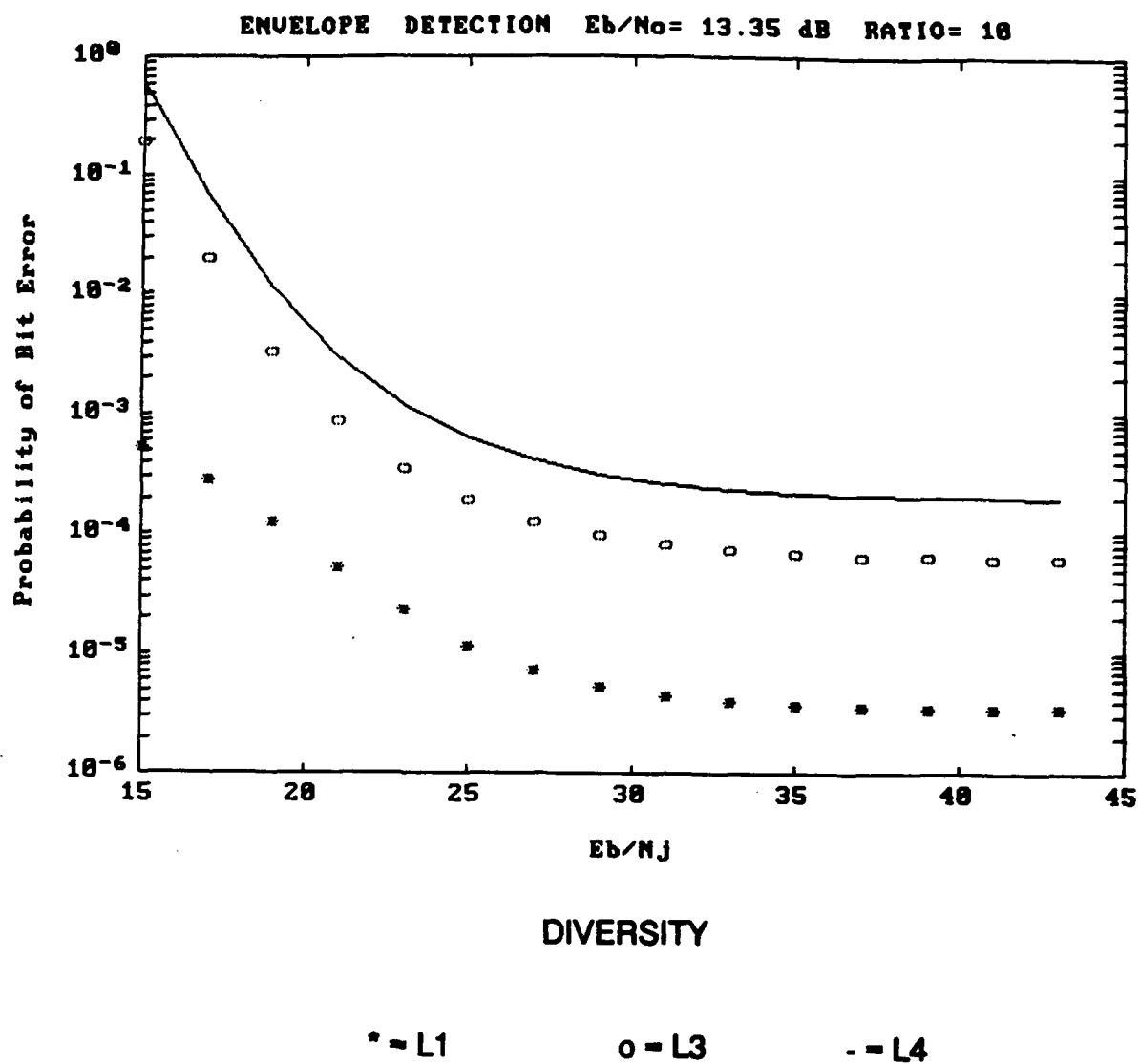


Figure 3.17. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10, and the worst case of $L=1$, 3 and 4.

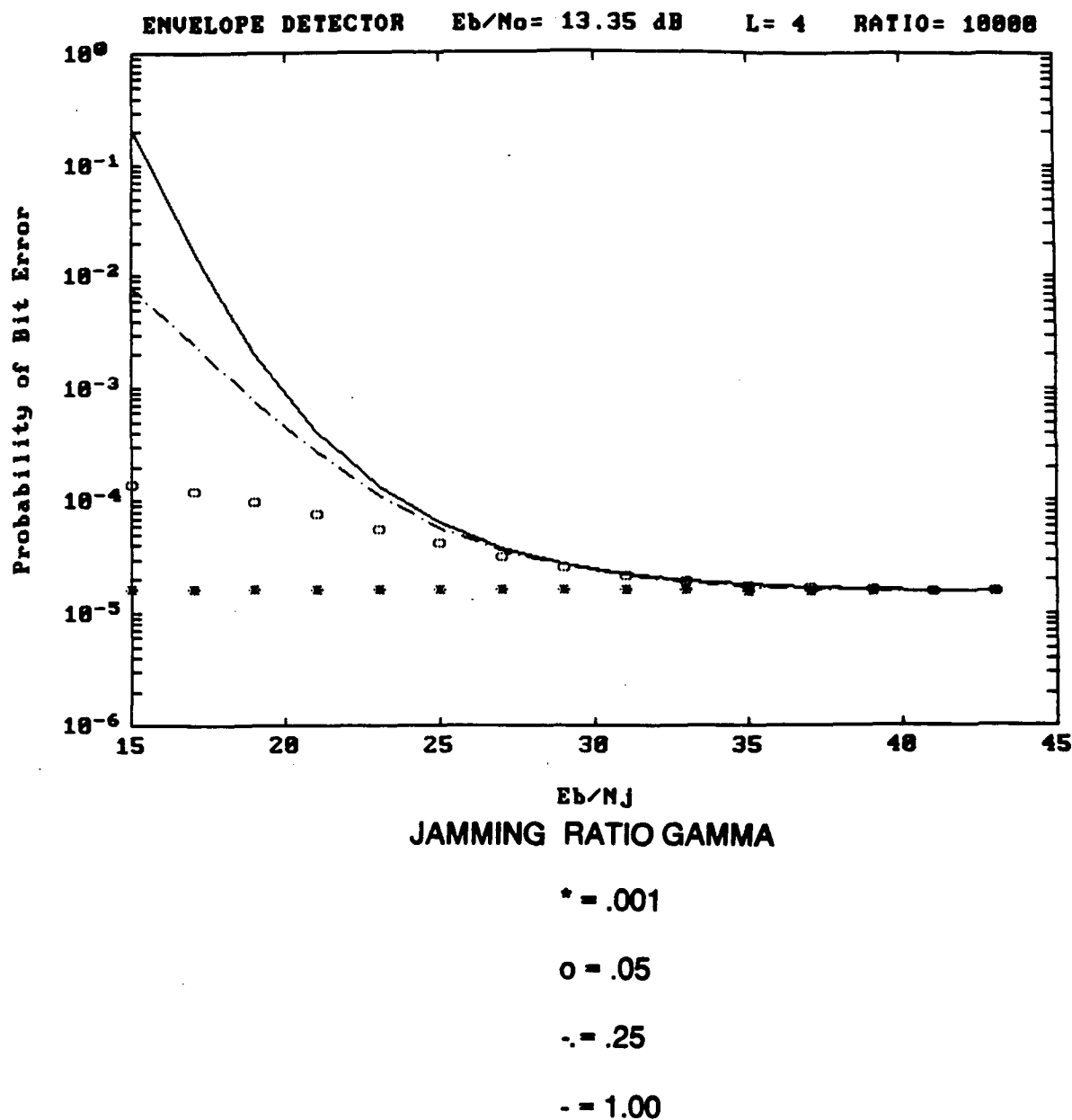


Figure 3.18. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO = 10000, $L = 4$ and different amounts of interference.

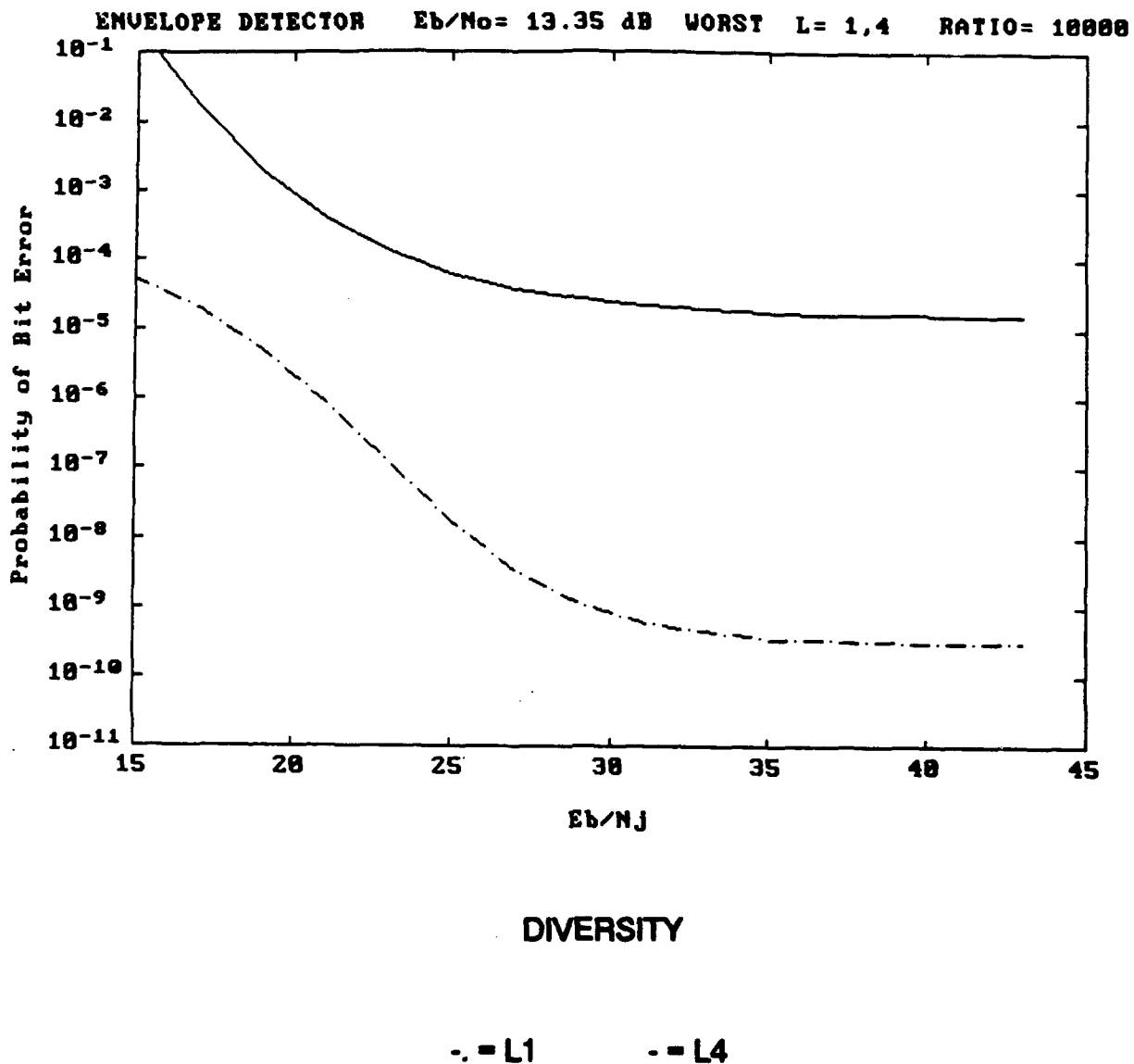


Figure 3.19. Performance of a FFH/NCBFSK/RS Receiver with Envelope detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10000, and the worst case $L=1$ and 4.

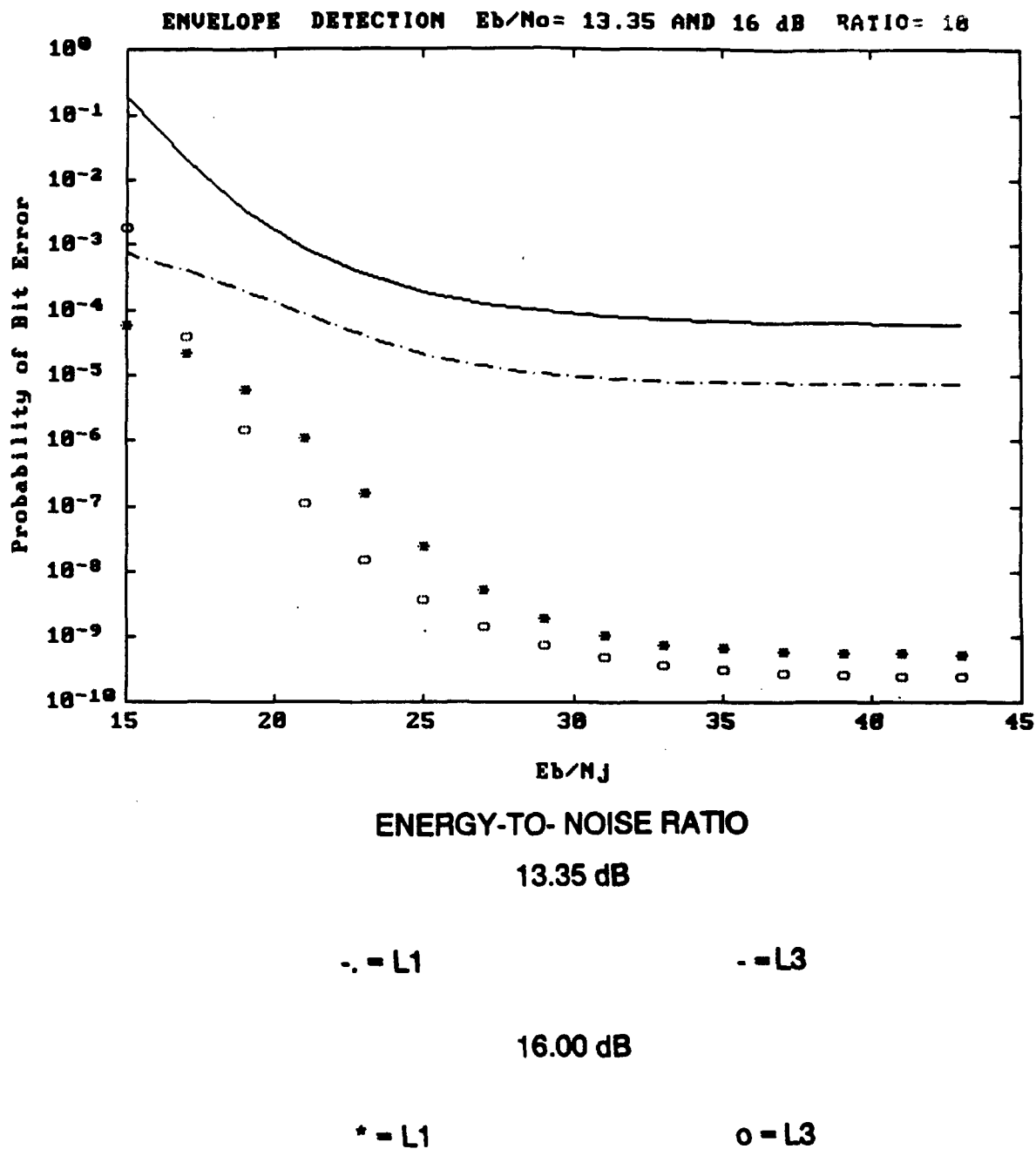


Figure 3.20. Comparison of the Performance of a FPH/NCBFSK/RS Receiver with Envelope detection, where Direct to Diffuse RATIO=10, $E_b/N_0=13.35$, and 16 dB and worst $L=1$ and 3.

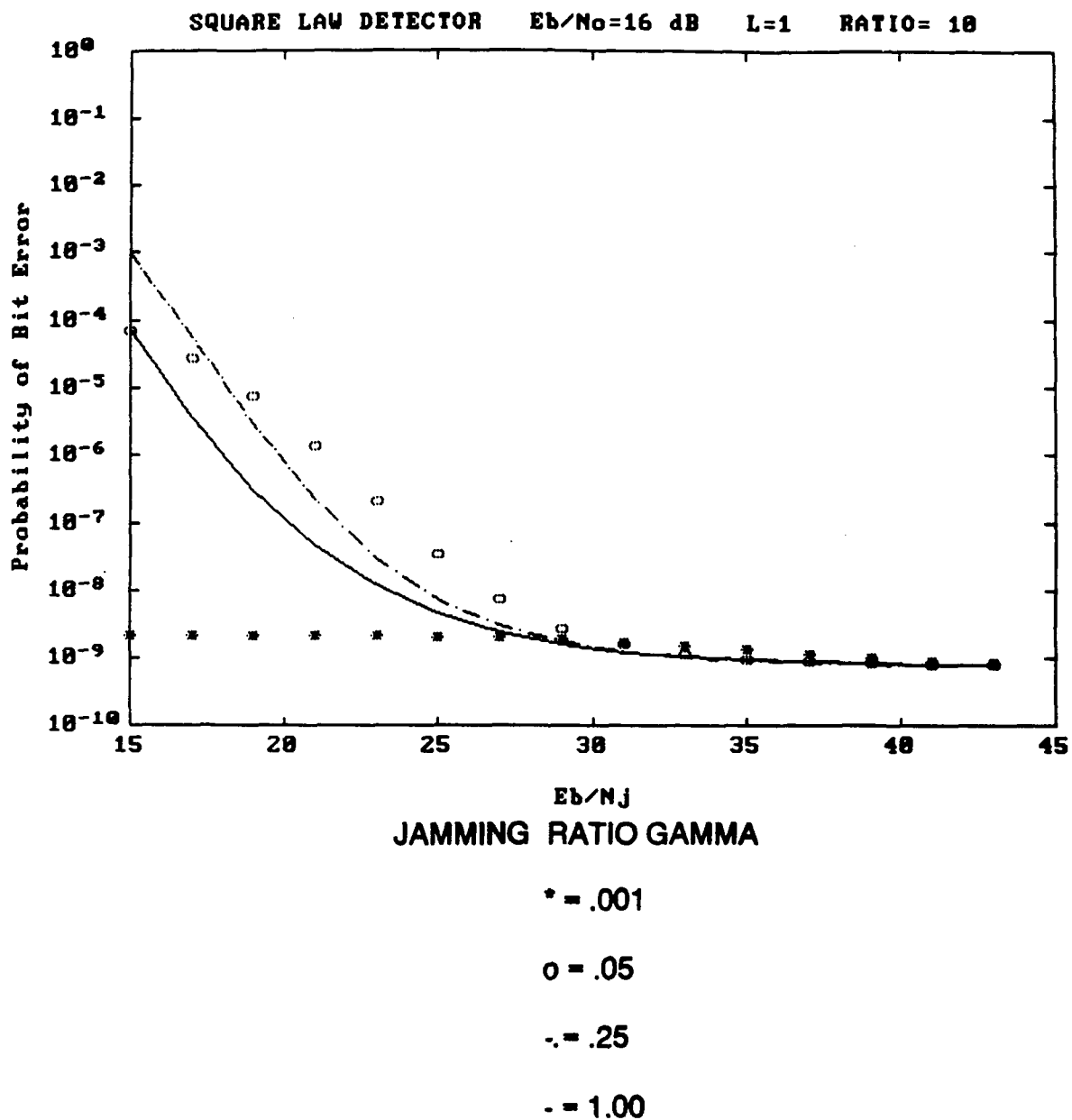


Figure 3.21. Performance of a FFH/NCBFSK/RS Receiver with Square Law detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10, and $L=1$.

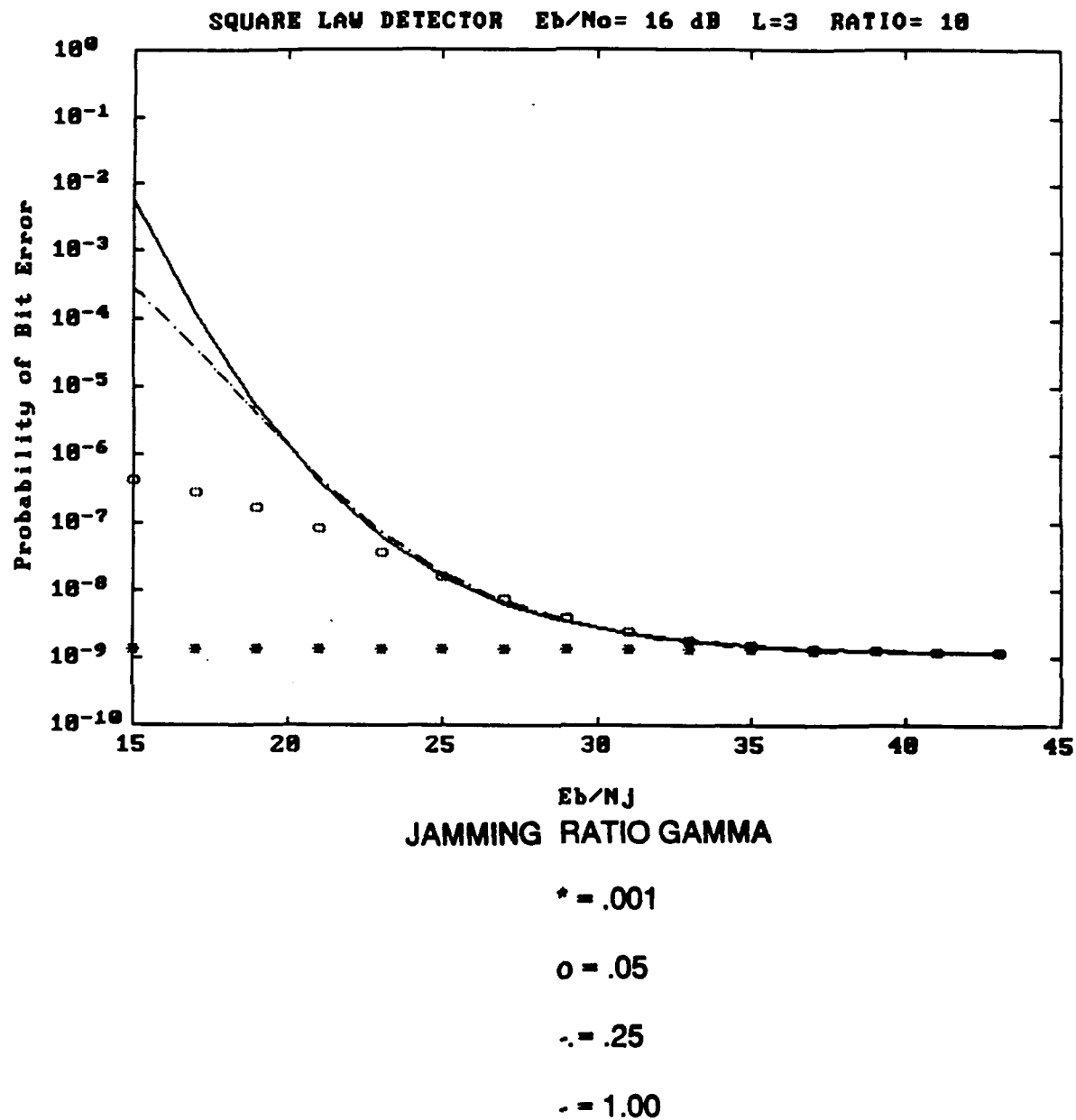


Figure 3.22. Performance of a FFH/NCBFSK/RS Receiver with Square Law detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10, and $L=3$.

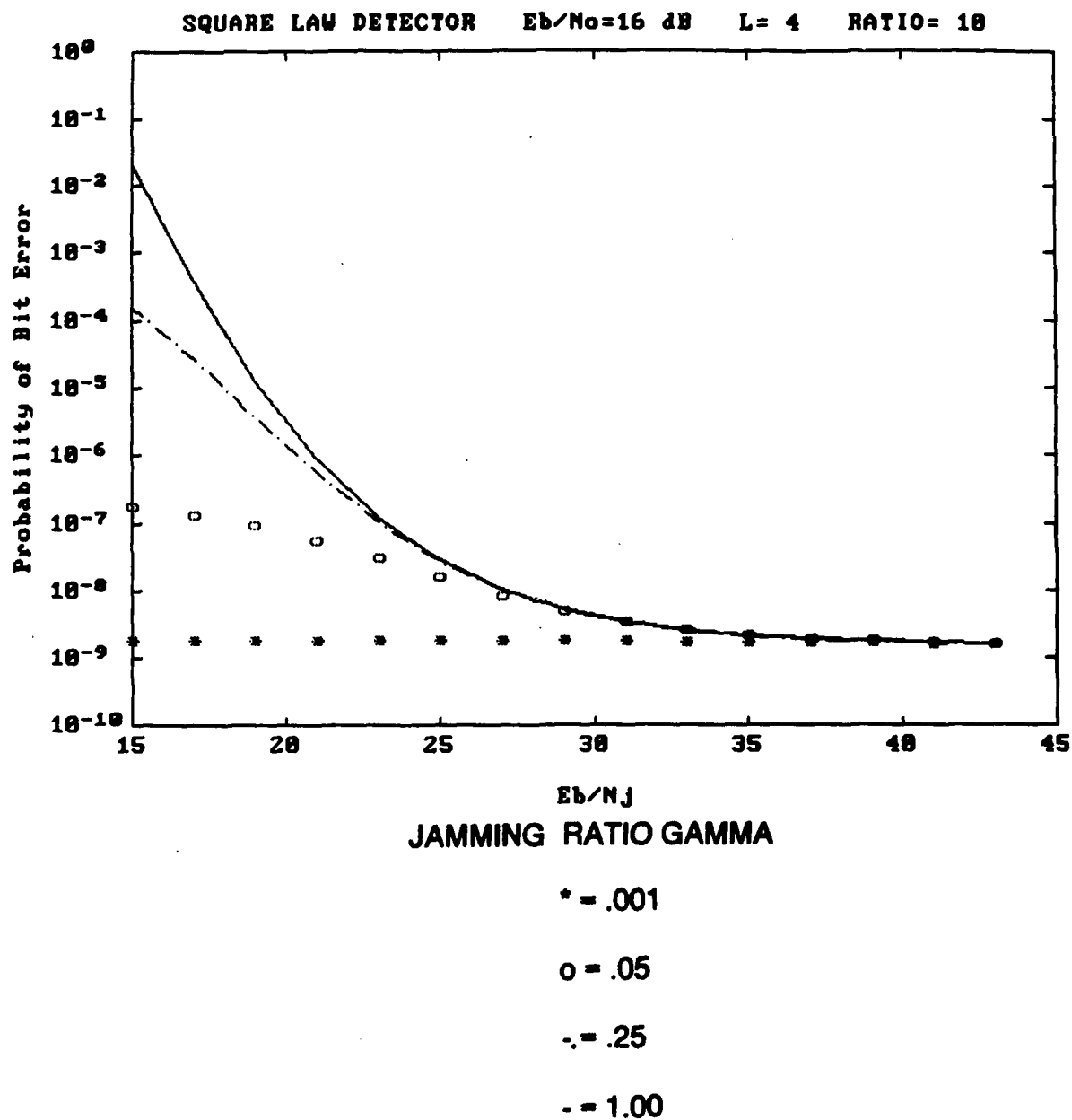


Figure 3.23. Performance of a FFH/NCBFSK/RS Receiver with Square Law detection, where $E_b/N_0=16$ dB, Direct to Diffuse RATIO=10, and $L=4$.

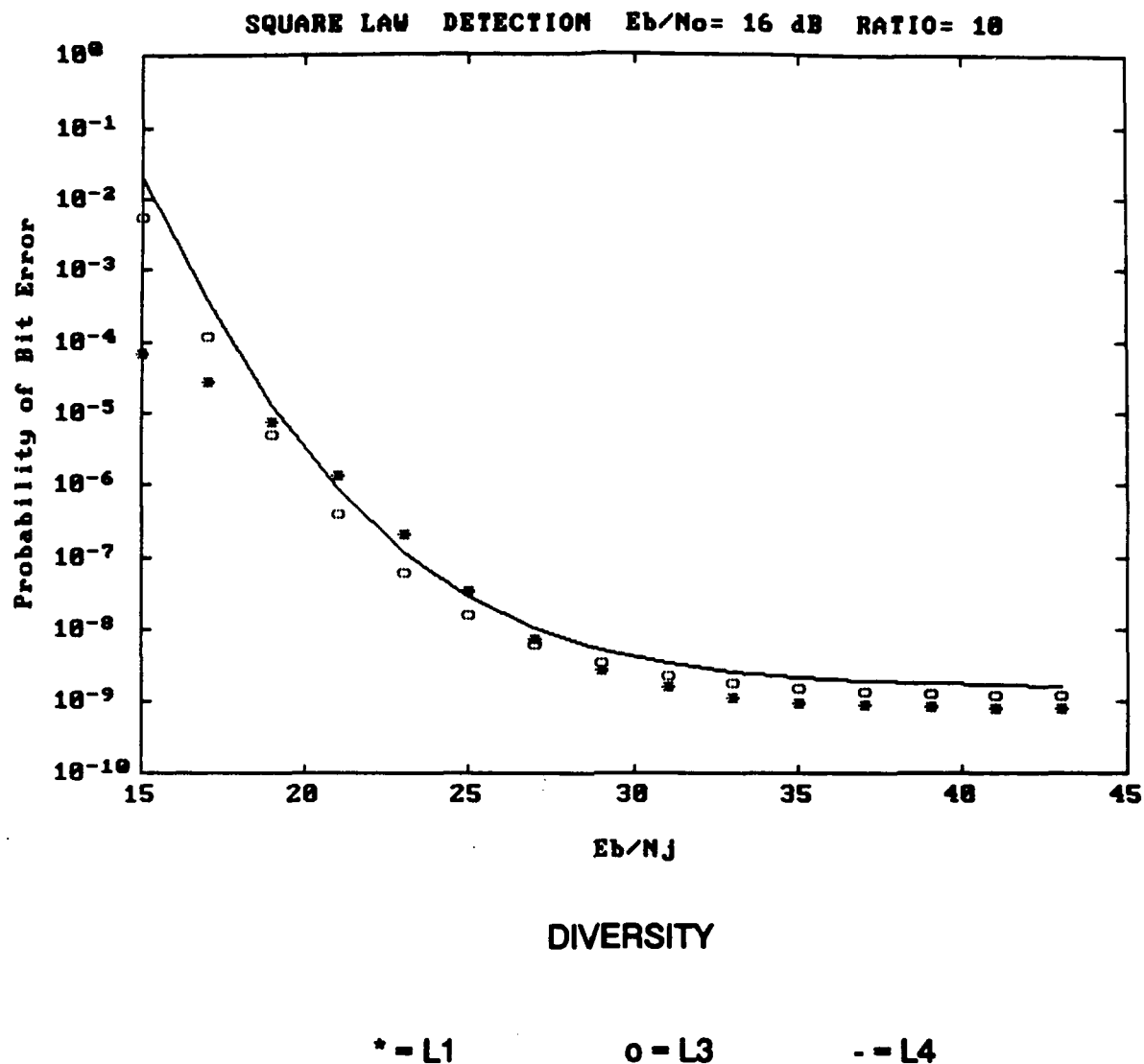


Figure 3.24. Performance of a FFH/NCBFSK/RS Receiver with Square Law detection, where $E_b/N_0 = 16$ dB, Direct to Diffuse RATIO=10, and the worst case of L=1, 3, and 4.

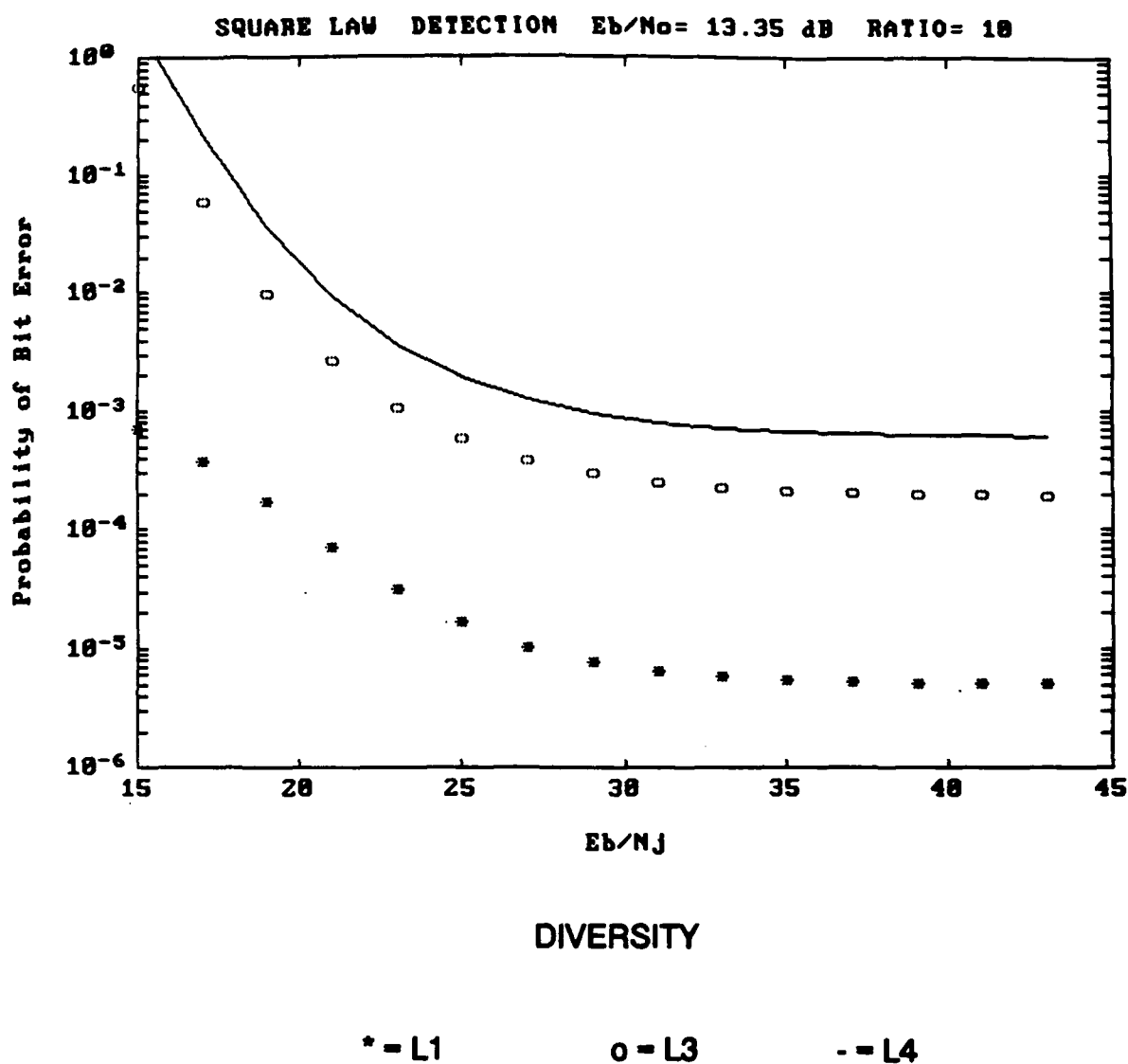


Figure 3.25. Performance of a FFH/NCBFSK/RS Receiver with Square Law detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10, and the worst case of $L=1, 3$, and 4.

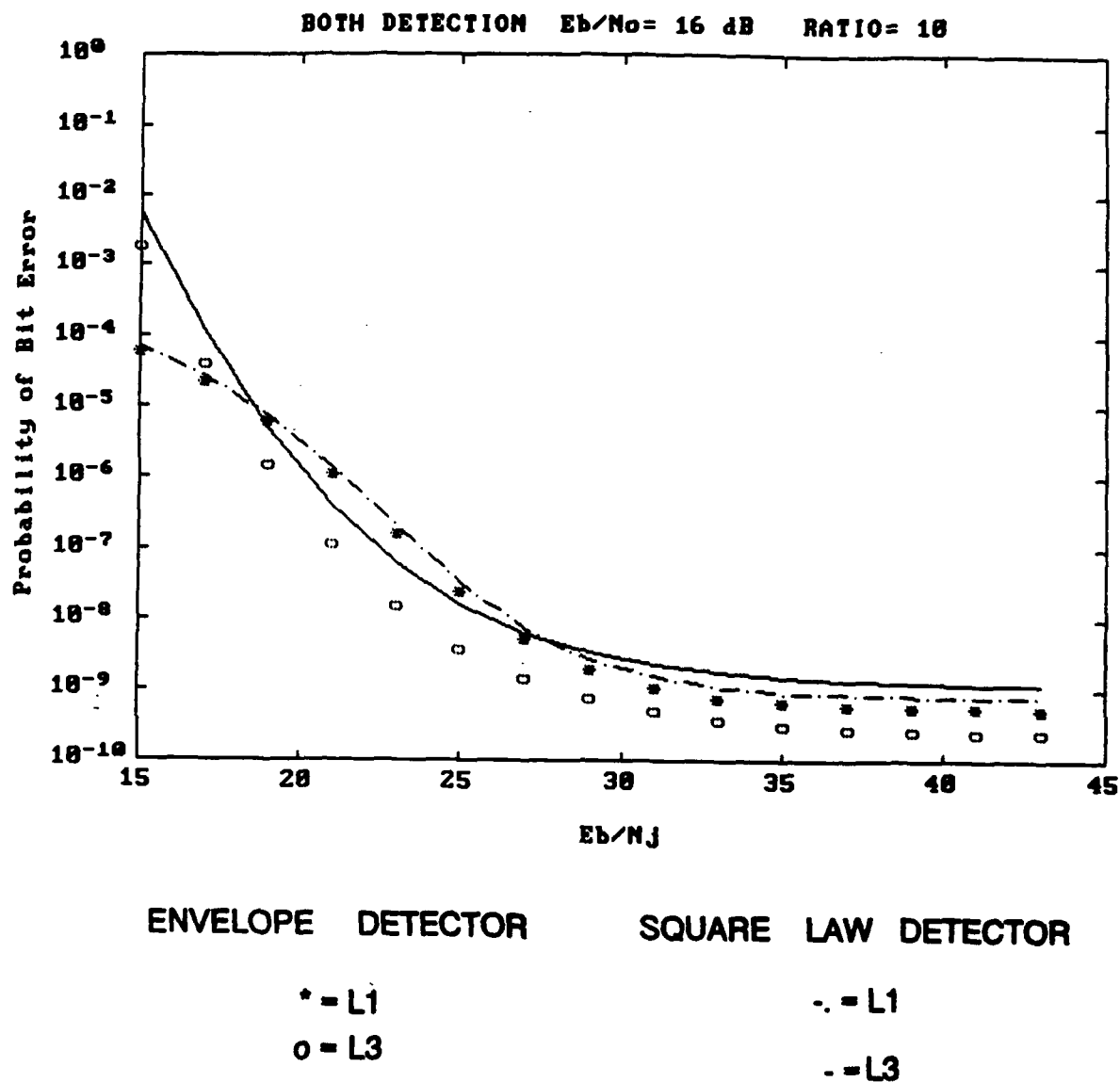


Figure 3.26. Comparison of the Performance of a FFH/NCBFSK/RS Receiver both detection, where $E_b/N_0 = 16$ dB, Direct to Diffuse RATIO=10, and the worst case of $L=1$ and $L=3$.

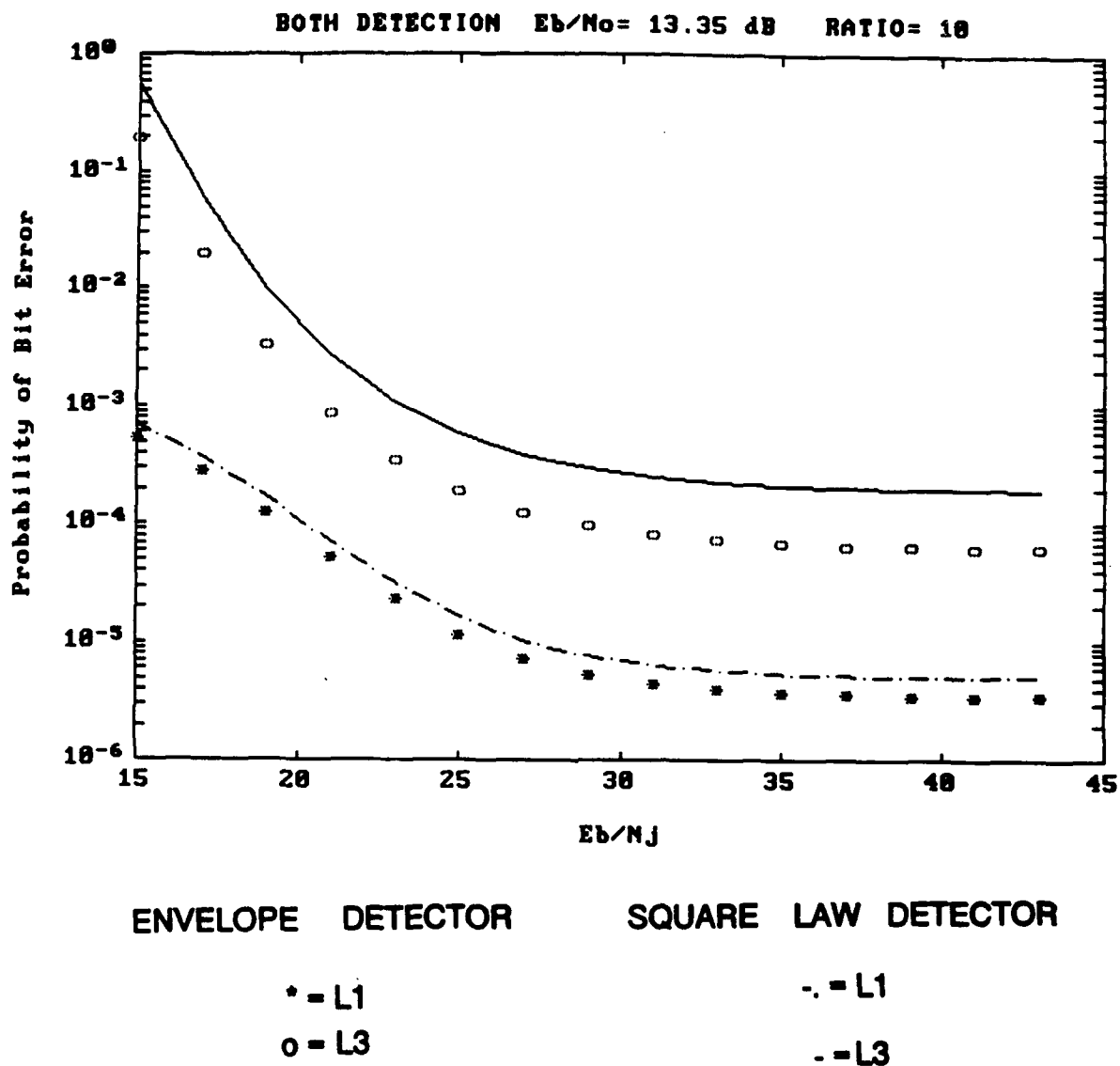


Figure 3.27. Comparison of the Performance of a FFH/NCBFSK/RS Receiver both detection, where $E_b/N_0 = 13.35$ dB, Direct to Diffuse RATIO=10, and the worst case of L=1 and L=3.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS.

This thesis has shown the performance of envelope and square-law detection of L-hops/symbol FH/BFSK for worst case partial-band jamming. The nonlinear ratio-statistic combining technique with forward error correcting coding is an effective strategy when combined with diversity to mitigate jamming effects.

Ratio-statistic combining soft decision receivers with forward error correcting coding outperforms the uncoded receiver for all cases of diversity, noise jamming interference, and channel fading.

The envelope detection optimum diversity level tends to be $L=3$ with a bit energy-to-jamming density ratio of 16 db; this corresponds to broadband jamming.

System performance is dramatically degraded when the bit energy-to-noise density ratio is reduced to 13.35 dB. The worst case performance for no diversity is better than higher orders; however, the worst case performance is better than that of the uncoded system under the same conditions.

The coded performance of square-law detection systems is not improved by diversity when jamming is broadband for all

channel types.

Comparision of the performance of envelope detectors and square-law detectors show that envelope detection performs better than square-law detection for all bit energy-to-jamming density ratios considered .

B. RECOMMENDATIONS.

The FFHSS/noncoherent BSFK receiver with ratio-statistic combining and forward error correcting coding has been evaluated for partial-band jamming and for different types of faded channels. This analysis should be extended to the general M-ary case. In addition, the ratio-statistic system should be simulated using some of the available communication simulation software packages.

APPENDIX

MATLAB SOURCE CODES

```
% The following source codes were developed by
% JOHN RILEY, 1990 and this codes were modified
% to implement the 1/2 VITERBI decoder algorithm.
% ENVMAIN.M Envelope Detection.
% This is the main source code that generates
% the decoded Pbe for the system with Ratio
% Statistic combiner and convolutional VITERBI
% decoder of rate 1/2.
%
r = 1/2;
RATIO = 'INPUT THE VALUE OF DIRECT TO DIFFUSE RATIO ';
n= 150;
Eb = 10^(x.xx); ' INPUT THE VALUE OF BIT ENERGY'
Ec = r*Eb
No = 1.0;
GAMMA = ' INPUT THE VALUE OF FRACTION JAMMING ' ;
L = ' INPUT THE DESIRE SYMBOL DIVERSITY ';
Eh = Ec/L;
DIFFUSE = Eh/(RATIO+1);
DIRECT = DIFFUSE*RATIO;
RHOn = DIRECT;
XIn = DIFFUSE;
for xx =1:21
    clear Pb
    EbNj = (xx-1)*2;
    Nj = 10^(-EbNj/10)*Ec;
    Nt = 1 + Nj/GAMMA;
    RHOi = DIRECT/Nt;
    XII = DIFFUSE/Nt;
    envpbe;
    PPbe(xx) = Pb;
    X(xx) = 10 * log10(Eb/Nj);
end
save PPbe;
save X;
clear
semilogy(X,PPbe);
title('Eb/No= dB      GAMMA=      L=      RATIO=      ');
xlabel('Eb/Nj');
ylabel('Probability of Bit Error');
```



```

%      ENVPBE.M  for rate code of 1/2
%      This program will determine the probability of error
%      as in equation 5 of Keller's paper. It is the
%      algorithm for the 1/2 VITERBI decoder for envelope
%      detection.
%
Pbee = 0;
for j = 0:L
convfad;
                                simperr;
Pbc(j+1)=Pbej*(fact(L)/(fact(j)*fact(L-j)))*GAMMA^j*(1-GAMMA
)^(L-j);
end
Pbee=sum(Pbc)
    d = 2*sqrt((1-Pbee)*Pbee);
    valor(xx)=d
        qq = 36*(d)^10;
        ww = 211*(d)^12;
        ee = 1404*(d)^14;
        Af = 11633*(d)^16;
        Pb= .5*(qq+ww+ee+Af);

```

```

%      FADNOINT.M      Envelope detection
%      This program will sample the probability density
%      functionm of the variable y, it generates the NON
%      JAMMED HOPS sequence and put it into and array f(y).
%
      clear f
for x = 1:n
    z = x - 1;
    y = -1+z/n;
    C = 2*(1+y)/((1+(1+y)^2)*(1+(1+y)^2+XIn));
    D = RHOn/(1+(1+y)^2+XIn);
    E = (1+y)^2/(1+XIn+(1+y)^2);
    K = RHOn*(1+(1+y)^2)/(1+XIn+(1+y)^2);
    f(x) = C*exp(-D)*(1+E*(XIn+K));
end
for x = 1:n+1
    z = x - 1;
    y = z/n;
    C = 2*(1-y)/((1+(1-y)^2)*(1+(1-y)^2*(1+XIn)));
    D = RHOn*(1-y)^2/(1+(1-y)^2*(1+XIn));
    E = 1/(1+(XIn+1)*(1-y)^2);
    K = RHOn*(1+(1-y)^2)/(1+(XIn+1)*(1-y)^2);
    f(x+n) = C*exp(-D)*(1+E*(XIn+K));
end
v = -1:2/length(f):1-2/length(f);

```

```

%      FADWINT.N      Envelope detection
%      This program will sample the probability density
%      function of the variable y, it generates the JAMMED
%      HOPS sequence and put it into an array f(y).
%
      clear f
for x = 1:n
    z = x - 1;
    y = -1+z/n;
    C = 2*(1+y)/((1+(1+y)^2)*(1+(1+y)^2+XIi));
    D = RHOi/(1+(1+y)^2+XIi);
    E = (1+y)^2/(1+XIi+(1+y)^2);
    K = RHOi*(1+(1+y)^2)/(1+XIi+(1+y)^2);
    f(x) = C*exp(-D)*(1+E*(XIi+K));
end
for x = 1:n+1
    z = x - 1;
    y = z/n;
    C = 2*(1-y)/((1+(1-y)^2)*(1+(1-y)^2*(1+XIi)));
    D = RHOi*(1-y)^2/(1+(1-y)^2*(1+XIi));
    E = 1/(1+(XIi+1)*(1-y)^2);
    K = RHOi*(1+(1-y)^2)/(1+(XIi+1)*(1-y)^2);
    f(x+n) = C*exp(-D)*(1+E*(XIi+K));
end
v = -1:2/length(f):1-2/length(f);

```

```

%      CONVHAD.M      ENVELOPE DETECTION
%      This routine generates the convolution of the Folded
%      convolutions for the jammed and non jammed HOPS.
%      fw represents the numerical evaluated PROBABILITY
%      DENSITY FUNCTION for the random variable W.
%
fadwint
h = 2/(length(f)-1);
if j==0
    fwi = [ 1 ];
elseif j==1
    fwi = f;
elseif j==2
    fwi = conv(f,f);
elseif j==3
    fwi = conv(conv(f,f),f);
elseif j==4
    fwi = conv(conv(conv(f,f),f),f);
elseif j==5
    fwi = conv(conv(conv(conv(f,f),f),f),f);
elseif j==6
    fwi = conv(conv(conv(conv(conv(f,f),f),f),f),f);
else
    fwi = error;
end
fadnoint
if (L-j)==0
    fwn = [ 1 ];
elseif (L-j)==1
    fwn = f;
elseif (L-j)==2
    fwn = conv(f,f);
elseif (L-j)==3
    fwn = conv(conv(f,f),f);
elseif (L-j)==4
    fwn = conv(conv(conv(f,f),f),f);
elseif (L-j)==5
    fwn = conv(conv(conv(conv(f,f),f),f),f);
elseif (L-j)==6
    fwn = conv(conv(conv(conv(conv(f,f),f),f),f),f);
else
    fwn = error;
end
fw = h^(L-1)*conv(fwi,fwn);

```

```

%      SIMPERR.M
%      This program uses Simpson's rule to find the area
%      under the array fw for y less than zero. This will
%      be the probability of bit error for a given # HOPS
%      jammed, Pbe(j) in a receiver using Ratio-Statistic
%      Combining. The result is in Pbej.
%
      areal=0;
      Pbej = 0;
for s = 2:(length(fw)-1)/2-1
      if round(s/2) == s/2
          areal = areal + 4*fw(s);
      else
          areal = areal + 2*fw(s);
      end
end
areal = areal + fw(1) +fw((length(fw)-1)/2);
Pbej = areal*h/3;

```

```

%      SQMAIN.M      SQUARE LAW DETECTION
%      This is the main source code that generates
%      the decoded Pbe for the system with Ratio
%      Statistic combiner and convolutional VITERBI
%      decoder of rate 1/2.
%
r = 1/2;
RATIO = 'INPUT THE VALUE OF DIRECT TO DIFFUSE RATIO ' ;
n= 150;
Eb = 10^(x.xx); ' INPUT THE VALUE OF BIT ENERGY'
Ec = r*Eb
No = 1.0;
GAMMA = ' INPUT THE VALUE OF FRACTION JAMMING ' ;
L = ' INPUT THE DESIRE SYMBOL DIVERSITY ' ;
Eh = Ec/L;
DIFFUSE = Eh/(RATIO+1);
DIRECT = DIFFUSE*RATIO;
RHOn = DIRECT;
XIn = DIFFUSE;
for xx =1:21
    clear Pb
    EbNj = (xx-1)*2;
    Nj = 10^(-EbNj/10)*Ec;
    Nt = 1 + Nj/GAMMA;
    RHOi = DIRECT/Nt;
    XIIi = DIFFUSE/Nt;
    sqpbe;
    PPbe(xx) = Pb;
    X(xx) = 10 * log10(Eb/Nj);
end
save PPbe;
save X;
clear
semilogy(X,PPbe);
title('Eb/No=   dB      GAMMA=      L=      RATIO=      ');
xlabel('Eb/Nj');
ylabel('Probability of Bit Error');

```

```

%      SQCORRE.M  for rate code of 1/2
%      This program will determine the probability of error
%      as in equation 5 of Keller's paper. It is the
%      algorithm  for the 1/2 VITERBI DECODER for the square
%      law detection.
%
Pbee = 0;
for j = 0:L
    sqcovfad;
                                simperr;
Pbc(j+1)=Pbej*(fact(L)/(fact(j)*fact(L-j)))*GAMMA^j*(1-GAMMA
)^(L-j);
end
Pbee=sum(Pbc)
    d = 2*sqrt((1-Pbee)*Pbee);
    valor(xx)=d
    qq = 36*(d)^10;
    ww = 211*(d)^12;
    ee = 1404*(d)^14;
    Af = 11633*(d)^16;
    Pb= .5*(qq+ww+ee+Af);

```

```

%      SQFADNOI.M      Square law detection
%      This program will sample the probability density
%      function of the variable y ,it generates NON JAMMED
%      HOPS sequence and put it into and array f(y).
%
      clear f
for x = 1:n
    z = x - 1;
    y = -1+z/n;
    C = (1/((2+y)*(XIn+2+y)));
    D = (1+y)/(XIn+2+y);
    E = -RHOn/(XIn+2+y);
    K = RHOn*(2+y)/(XIn+2+y);
    f(x) = C*exp(E)*(1+D*(XIn+K));
end
for x = 1:n+1
    z = x - 1;
    y = z/n;
    C = 1/((2-y+XIn*(1-y))*(2-y));
    D = RHOn*(1-y)/(2-y+XIn*(1-y));
    E = 1/(2-y+XIn*(1-y));
    K = RHOn*(2-y)/(2-y+XIn*(1-y));
    f(x+n) = C*exp(-D)*(1+E*(XIn+K));
end
v = -1:2/length(f):1-2/length(f);

```



```

%      SQFADWIN.M      Square law detection
%      This program will sample the probability density
%      function of the variable y ,it generates the JAMMED
%      HOPS sequence and put it into and array f(y).
%
      clear f
for x = 1:n
    z = x - 1;
    y = -1+z/n;
    C = (1/((2+y)*(XIi+2+y)));
    D = (1+y)/(XIi+2+y);
    E = -RHOi/(XIi+2+y);
    K = RHOi*(2+y)/(XIi+2+y);
    f(x) = C*exp(E)*(1+D*(XIi+K));
end
for x = 1:n+1
    z = x - 1;
    y = z/n;
    C = 1/((2-y+XIi*(1-y))*(2-y));
    D = RHOi*(1-y)/(2-y+XIi*(1-y));
    E = 1/(2-y+XIi*(1-y));
    K = RHOi*(2-y)/(2-y+XIi*(1-y));
    f(x+n) = C*exp(-D)*(1+E*(XIi+K));
end
v = -1:2/length(f):1-2/length(f);

```

```

%      SQCOVFAD.M      SQUARE LAW DETECTION
%      The routine generates the convolution of the Folded
%      convolutions for jammed and nonjammed HOPS.
%      fw represents the numerical evaluated PROBABILITY
%      DENSITY FUNCTION for the random variable W.
%
sqfadwin
h = 2/(length(f)-1);
if j==0
    fwi = [ 1 ];
elseif j==1
    fwi = f;
elseif j==2
    fwi = conv(f,f);
elseif j==3
    fwi = conv(conv(f,f),f);
elseif j==4
    fwi = conv(conv(conv(f,f),f),f);
elseif j==5
    fwi = conv(conv(conv(conv(f,f),f),f),f);
elseif j==6
    fwi = conv(conv(conv(conv(conv(f,f),f),f),f),f);
else
    fwi = error;
end
sqfadnoi
if (L-j)==0
    fwn = [ 1 ];
elseif (L-j)==1
    fwn = f;
elseif (L-j)==2
    fwn = conv(f,f);
elseif (L-j)==3
    fwn = conv(conv(f,f),f);
elseif (L-j)==4
    fwn = conv(conv(conv(f,f),f),f);
elseif (L-j)==5
    fwn = conv(conv(conv(conv(f,f),f),f),f);
elseif (L-j)==6
    fwn = conv(conv(conv(conv(conv(f,f),f),f),f),f);
else
    fwn = error;
end
fw = h^(L-1)*conv(fwi,fwn);

```

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